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Abstract: ***The stomatognathic system is a very complex structure that includes the temporomandibular joint, masticatory muscles, teeth, gingiva, tongue, and pharynx. In this structure, maximum bite force measurement has been an important field of study in the diagnosis and treatment of diseases caused by disorders related to chewing habits. Objectives: Since existing measurement systems are expensive and impractical, researchers are in search of better systems. In this study, a modular and low-cost system has been developed to measure the bite forces accurately. Materials and Methods: The sensor data read by the microprocessor were converted to force values by the optimum curve fitting methods and results are instantly displayed on the user screen. The five different curve fitting functions were used to obtain the best results according to the goodness-of-fit statistics. The exponential equation was selected as the curve fitting method from the results of the goodness-of-fit statistics. The results were verified and system was calibrated by comparing the applied force values and system results. Results: In this study, a low cost, mobile, accurate and precise measurement system which has high reproducibility has been developed via basic engineering instruments. Conclusions: Simple and efficient design of the measurement system gives opportunity to use different sensors in future studies.***

Keywords: Maximum Bite Force, Sensors, Curve Fitting.

1. Introduction

T Maximum bite force (MBF) is a frequently used method in the examination of masticatory mechanics in dentistry and in determining disorders related to masticatory system and occlusal problems [1, 2]. It is also a preferred method for post-treatment evaluation and comparison of alternative treatment method [3, 4]. In order to use these measurement results effectively in clinical studies, it is very important to use accurate and precise measurement systems [5].

Flanagan et al., measured the bite force by connecting the FlexiForce (Tekscan) sensor to a multimeter. They obtained the force values from the resistance values read via multimeter [6]. Fernandes et al. made measurements using polymer pressure sensors [1]. They obtained the force values by processing the electrical signals of the sensor output. Fastier-Wooller, J. et al. conducted a strain measurements using a strain gauge system [7]. Thongudomporn et al. made measurements using the FSR (Interlink, USA) sensor, oscilloscope and computer [8]. They converted the sensor output values to force values with the multi-term regression equation. Rane et al. used load cells for bite force measurements [9]. They designed a system consists of a load cell, an amplifier circuit and a computer for processing the results and display them. Umesh et al. developed and used a fiberoptic-based FBG sensor for force measurements [10].

In this study, a bite force measurement system was designed in order to use in diagnosis and treatment of diseases caused by disorders related to chewing habits. For this aim, a modular and low-cost system was developed to make the measurements accurately. This system consists of sensor, power supply and voltage divider circuit, microcontroller board and display units. In order to obtain the force values from the sensor data certain loads were applied to the developed sensor system then digital sensor values were displayed and recorded. The curve fitting analysis is conducted in MATLAB® software to obtain the force values by using applied loads and corresponding sensor values. The correlation between sensor data and force values is expressed by exponential, Gauss, Fourier and polynomial functions using "Curve Fitting Toolbox" of MATLAB®. The exponential function is selected due to the fitting statistics such as sum of squares due to error (SSE), R-square, and Root mean squared error (RMSE).

2. Materials and Methods

In this study, a modular and low cost system has been developed for measuring the bite forces accurately and precisely. The measurement system consists of two main structures. The first is a microprocessor for data acquisition, and the second is a sensor system design that can perform accurate and precise measurements. In the sensor system, a commercially available FlexiForce Pressure Sensor (Tekscan - USA) is used for the compression forces and shown in Figure 1.

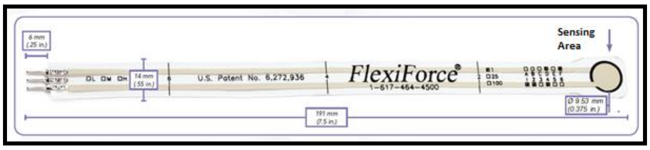

Figure 1: Flexiforce pressure sensor dimensions

The pressure sensor, which is 191 mm long, 14 mm wide and 0.203 mm thick, has a circular sensing area with a diameter of 9.53 mm and is coated with polyester. The sensor is capable of measuring up to 400 N and has high linearity (error <± 3%), high response speed (<5 microseconds). Also, the sensor, which can operate at temperatures between -40 ° C and 60 ° C, is slightly affected by sensor temperature changes. (Change rate = 0.36% / ºC).

The sensor has a 9.53 mm diameter sensing area and it is important to apply the forces only to this area for accurate measurements. In order to achieve this, metal washers were attached to both surfaces of the sensing area of the sensor. In addition, two supporting components made of PE 1000 plastic were used to direct the forces vertically to washers and to prevent damage to other parts of the sensor. PE 1000 plastic material was chosen to provide sufficient mechanical properties (yield strength 19 MPa, 5% nominal tensile strength 10.7 MPa) in order to prevent plastic deformation under applied loads. In addition, PE 1000 plastic materials are used in the food industry due to low moisture absorption. Considering the conditions in mouth, it is very important for the reliability of the tests. Sensor system design as a biting apparatus is given in Figure 2.

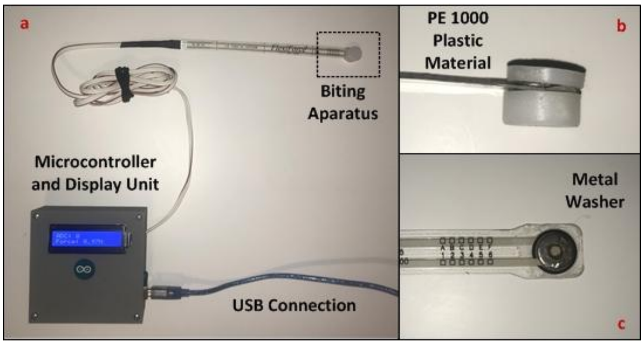

Figure 2: (a) measurement system (b) biting apparatus (c) biting force sensor with metal washers

Measurement system is consisting of; sensor, power supply and voltage divider circuit, microcontroller board and display units. Flow chart of the working mechanism is shown in Figure 3. When the force is applied to the sensor, analog signal depending on the applied force is transmitted to microcontroller. This analog signal is converted to digital values with Arduino UNO development board and can be processed in computer environment. Then, results are displayed on user screen.

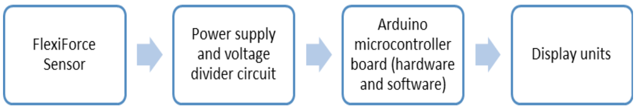

Figure 3: Flow chart of the measuring system

Analog signals (DC voltage, 0-5 V) from the sensor circuit are converted to digital values (ADC, 0-1023) thanks to the hardware features of the development board (10-bit ADC / Analog to Digital Converter). Via the software prepared for microcontroller board, these digital values were processed and force values were obtained. The results can be seen instantly on the LCD screen, and can be displayed and stored in a computer environment via USB connection.

In order to obtain the force values from the sensor data and test the accuracy of the system, certain loads were applied to the developed biting apparatus at a tensile and compression test device with a 2kN load-cell (INSTRON 5944). Different loads gradually increasing from 25N to 450N were applied to system, then digital values displayed on screen were recorded. This loading series was repeated 10 times in order to provide the repeatability of the sensor measurement. The mean and standard deviation of the values for each load stage were calculated. These values are given in Table-1. Standard deviation values decreased with increasing load. The operating range for the maximum bite force measurement is usually 250-450 N. In this range, the standard deviation value varies between 3,734-0,707. It is seen that these values are at the desired level for the designed measurement system.

Table 1: Applied loads and obtained digital values

Applied Load (N)	Average Digital Value (ADC)	Standard Deviation (ADC)
25	645,625	10,268
60	762,75	6,112
100	820	7,241
150	858,625	4,798
200	883,5	4,772
250	899,5	3,734
300	913,5	3,045
350	924,875	2,26
400	933,75	1,201
450	941,25	0,707

MATLAB® software was used to obtain the force values by using average digital values corresponding to the applied loads. MATLAB® is software designed for scientific calculations, including numerical calculation, data analysis and graphical representation, simulation and programming. To find the best curve fitting method, the best and basic method is evaluating the goodness-of-fit statistics (GOFS) which show that how well the model fits the experimental results. MATLAB® supports the SSE, R-square and RMSE as GOFS.

SSE is total deviation of experimental values from the predicted values and given by Equation (1), where e_i is the experimental value, p_i is the corresponding predicted value and w_i is the weight scale factor. As a fitness indicator, a SSE value close to 0 means a good fit.

$$SSE = \sum_{i=1}^{n} w_i \left(e_i - p_i\right)^2 \quad (1)$$

R-square is a statistics that shows how successful the fit is. Also, R-square given by Equation (2) can be defined as the square of the correlation of the experimental values and corresponding predicted values [11]. R-square value closer to 1 indicates that a greater proportion of variance is accounted for by the curve fitting equation.

$$R-square = \frac{\sum_{i=1}^{n} w_i (p_i - \bar{e})^2}{\sum_{i=1}^{n} w_i (e_i - \bar{e})^2} \quad (2)$$

RMSE is the standard error of the regression and estimate of the standard deviation of the random component in experimental data. RMSE can be calculated with Equation (3) where v is the residual degrees of freedom. v is defined in equation (4) where n *is* the number of response values and

m is the number of fitted coefficients. For evaluating the goodness of fit, the closer the RMSE value is to zero, the more successful the model is.

$$RMSE = \sqrt{\frac{SSE}{v}} \tag{3}$$

$$v = n - m \tag{4}$$

With "Curve Fitting Toolbox" of MATLAB®, the correlation between sensor data and force values is expressed by exponential, Gauss, Fourier and fourth and fifth degree polynomial functions. GOFS of the functions were given in Table 2.

Table 2: GOFS of the curve fitting functions

Goodness-of-fit Statistics	Exponential	Gauss	Fourier	Polynomial 4th Degree	Polynomial 5th Degree
The sum of squares due to error(SSE)	9,805	9,73	26,96	36,96	10,73
R-square	0,9999	0,9999	0,9999	0,9999	0,9999
Root mean squared error (RMSE)	1,278	1,56	2,596	2,322	1,638

As seen in Table 2, exponential and Gauss functions have lower SSE and RMSE values than the others. Since, they provide better fit, exponential and Gauss functions were analyzed and defined in general form in Equations (5, 6), respectively.

$$f(x) = a_1 \times e^{b_1 \times x} + a_2 \times e^{b_2 \times x} \tag{5}$$

$$f(x) = a_1 \times e^{-\left(\frac{(x-b_1)}{c_1}\right)^2} + a_2 \times e^{-\left(\frac{(x-b_2)}{c_2}\right)^2} \tag{6}$$

In the equations (5, 6), x is the digital value read from the sensor and $f(x)$ is the corresponding force value in Newtons. a, b, c are the constants in the equation were calculated by the curve fitting method. Exponential and Gauss functions have close SSE values, but exponential function was selected for curve fitting because it has lower RMSE value and can be defined with less coefficients. Also, it is preferred in order to use it correctly and effectively with the developed software and microcontroller board. For equation (5), the constant coefficients were calculated by MATLAB®, as $a_1 = 7{,}659x10^{-7}$, $b_1 = 0{,}02092$, $a_2 = 0{,}3256$, $b_2 = 0{,}006689$. Fitting curve seen in Figure 4 was plotted according to equation (5) and calculated coefficients. In Figure 4, it can be seen that fitting curve pass through all data points. In addition, the residual error graph obtained from the exponential curve fitting method is given in Figure 5. It is seen that the residual error is a maximum of about 0.5%.

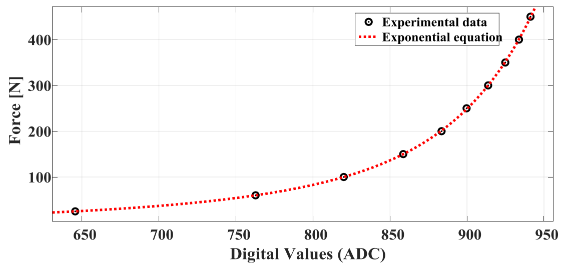

Figure 4: Fitting curve

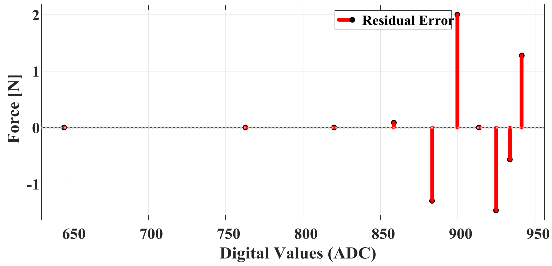

Figure 5: Residual error

Via developed bite force measurement device, maximum bite force measurement can be made in individuals. For measurements, biting apparatus should be placed on the occlusal surface of the 1st molar tooth in the mandibula as shown in Figure 6. This region has been identified as the center with the highest bite force [12]. This system was used to compare the treatment methods of bruxism in PhD thesis study of Kaya DI, The Oral and Maxillofacial Surgery Clinic, Faculty of Dentistry, Selcuk University.

Figure 6: Maximum biting force measurement [13]

3. Results

In this study, a low cost, mobile, accurate and precise measurement system which has high reproducibility has been developed via basic engineering instruments. The sensor data processed by the microprocessor board were converted to force values by the most appropriate curve fitting methods. In order to use it correctly and efficiently in the development card, exponential function which has better GOFS compared to other methods was selected. For the experimental data and the fitting curve, the comparison was made using multiple coefficient (R-square = 0.9999). It was also found that the maximum residual error was about 0.5%.

4. Discussion

Simple and efficient design of the measurement system gives opportunity to use different sensors in future studies. This makes more precise and higher force measurements possible. Furthermore, the developed software is open to improvement and also suitable for the use of possible different curve fitting methods.

5. Conclusion

We believe that this study has made significant contributions and innovations in the dental field. Also, simple and efficient design of the measurement system gives opportunity to use different sensors in future studies.

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Author Profile

Doğan Ilgaz Kaya received the DDS. and PhD. degrees in Dentistry and Maxillofacial Surgery from Selçuk University in 2013 and 2019, respectively. During 2013-2020, he worked for Health Ministry of Republic of Turkey as an oral surgeon. He now still work on same position at Konya Oral and Dental Health Hospital.