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Original Research

Smart Gnathometer for Bite Force Measurement

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ABSTRACT

Bite force measurement on teeth is one of the crucial factors contributing to the development of advanced technology and longevity in the fabrication of prosthesis. Throughout the years, many researchers have developed devices to measure and analyse the maximum bite force. However, the innovations of the devices have some drawbacks, such as precision, measurement accuracy and cost-effectiveness. Moreover, some of the devices may affect the health of patients due to the usage of hazardous material. Therefore, a non-hazardous gnathometer has been innovated in the study to precisely measure and analyse the maximum bite force of dentures. A 3D model of the new gnathometer was designed using CATIA V5 and fabricated using a Fused Deposition Modelling (FDM) machine. The gnathomether also consisted of electronic parts, such as an ESP32 and Arduino Nano as a microcontroller, and a flexible force sensor to accurately measure the bite force measurement. A calibration test was carried out on this innovation to measure the accuracy, drift presence and consistency of bite force. This study demonstrated that the force mappings were directly proportional to the voltage and has shown that the resistance gradually decreases until it reaches a minimum or steady state as the force increases. This research on the calibration of force was valid as the accuracy calculated was a minimum of 94.80% with a maximum accuracy error of 5.20%, resulting in high accuracy and reliable results. This study suggested that the gnathometer can analyse the maximum bite force of dentures and is one of the best approaches to obtain precise and accurate bite force measurements. This research can improve dentures studies in the dental industry using the Internet of Things (IoT) technology embedded in the system and real-time bite force monitoring.

INTRODUCTION

Individual bite force analysis has become one of the essential health indicators widely used in dentistry to help clinicians and researchers assess the function and efficacy of the masticatory system, generally known as the chewing motion of patients (Fernandes et al., 2003). The chewing process happens when there is an opening, closing, and grinding of jaw movement supported by the masticatory muscles. The structural mouth elements such as teeth, nerves, bones and muscular systems action from the masticatory structure will influence the bite force values analysed as reported in several studies (Rentes et al., 2002). Generally, the bite force can be described as the force exerted by the masticatory muscles during tooth occlusion (Verma et al., 2017). The bite force evaluation and analysis can assess the efficacy of various dental treatment such as orthodontics, prosthodontics, and implant dentistry. Alternatively, it can also be used to study on malocclusion and temporomandibular disorder of the masticatory system (Verma et al., 2017). Confounding factors have been reported to affect the maximum bite force measurement, such as age, gender, weight, height and periodontal support of teeth of denture patients, leading to various research conducted in this field (Roffie et al., 2020).

The maximum bite force directly impacts patients' meal selection, which is crucial for preserving masticatory function and patients' wellness (Fayad et al., 2018). Reduced number of occluding teeth with poor tooth supporting structure becomes

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disadvantageous and compromised the masticatory function. Mostly, they will avoid hard to chew food such as red meat, poultries and high fibrous vegetable as their chewing efficiency is decreased thus having difficulty to crunch the food bolus. This eventually will affect their general health. Previous research has reported that nearly 30% of patients that have been affected by loss of teeth and wearing removable prostheses, have various problems with their dentures, especially the mandibular denture with regards to retention, stability and pain while eating food (Fayad et al., 2018). Despite of these problems, many people wear complete dentures with good quality denture adhesives to improve retention and strength as the bond between the tissues and dentures is strengthened (Psillakis et al., 2004).Apart from masticatory problem, the confidence level of edentulous patients is gradually decrease and their character will change as they meet people in public. As the age of a person increases, the supporting structures such as the alveolar bone, periodontal ligaments and facial muscular activity will undergo functional changes, which will then cause a further reduction in bite force and loss of teeth (Chong et al., 2016).

In the history of the development of the bite force recorder, the first device used to measure bite force was developed by Borelli, known as a gnathodynamometer. Different weights were attached to the cord of the appliance and passed over the mandibular molar teeth in an open position (Koc D et al., 2010). Recent developments in dentistry have led to various methods used to study and evaluate the maximum bite force of denture patients with the help of electronic systems, mechanical systems or a combination of both approaches. The devices vary from a simple setup of using a device with a simple spring to a complex combination of mechanical and electronic devices (Fernandes et al., 2003). Devices have been developed and studied where electronic methods were derived from conventional mechanical devices which has resulted in more effective and sensitive results (Ortug, 2002).

Recently in the dental industry, researchers have shown an increased interest in using a force-sensing resistor as the main approach to the development of a gnathometer. It functions by allowing evaluation of static and dynamic forces when applied to the surface of sensors (Sadun et al., 2016). The main factor that affects the responses of the force-sensing resistor is its electrical resistance. As observed, when the force is applied to the sensor, the electrical resistance will gradually decrease until it reaches a steady-state position (Higashisaka et al., 2019). Recent studies have stated that the gnathometer which had been developed to measure the maximum bite force is accurate and precise enough to measure load and pressure purposes (Fløystrand et al., 1982). Unfortunately, questions have been raised about the drawbacks of the previous devices regarding precision and inaccuracy in measurement. Many of the device also said to be not user-friendly and not being cost-effective. Some researchers even described on a long-term effect on patients due to hazardous and non-biodegradable materials used in the fabrication of the device. All these issues lead to in favourable usage of the gnathometer device in the field of dentistry in that time.

In recent years, the device has been improvised where the use of sensors has been integrated to evaluate the bite force of patients due to its accuracy and precise results. One of the most significant devices that has been continuously used in the dental industry is the advanced technology of T-Scan II, which can be used to analyse and display occlusal contact information by pressure-sensitive film built in the device (Nalini and Sinha, 2018). Compared to the older T-Scan I, it has improved in terms of more contacts recorded during the occlusal test (Da Silva Martins et al., 2014). The T-Scan devise, despite its long clinical success, is expensive from the financial point of view and may give inaccurate results as the force from sharp teeth concentrated at the surfaces of the sensors may cause damage to it.

Furthermore, one major issue in gnathometer research was the concern with few of the earlier invented devices which could not analyse high strength bite force. For example, a custom stainless steel gnathometer can only measure force up to 196.2 Newtons, which may become one of the disadvantages as average human occlusal force are beyond the device limit (Roffie et al., 2020). Lastly, questions have been raised about the safety of prolonged use of the gnathometers fabricated from hazardous materials. Some of the devices which had been made from stainless steel were not good enough to be used by humans as they may have caused harm to the users. Therefore, this study aimed to develop a more accurate and precise gnathometer device. A device that integrates a smart wireless gnathometer with electronic circuits and mechanical elements which are more compact and easily accessible to users of all ages.

MATERIALS AND METHOD

Structural Design of the Gnathometer

In the past decades, various methods have been used to develop and fabricate gnathometer devices. Previous studies have become the source of design and creation of a simpler and more effective gnathometers, as well as upgraded shape to solve the design problems. One of the major problems with previous devices is that the force sensor or the wires that connect with the force sensor may touch the cheeks of the patients during bite force testing. A specific problem in the previous design is that during bite force testing at the front teeth, the teeth did not fit well nor firm on the bite place, which may affect the result recorded. Therefore, this study has been carried out to overcome the problems faced. The device was designed and fabricated using a 3D-printer using polylactic acid (PLA), as demonstrated in Figure 1(a). PLA is defined as a biodegradable polyester material from renewable resources such as tapioca roots, sugarcane, or corn starch, thus exhibiting the non-toxic properties and biocompatible to patients. For the ease of patients during bite test, the range between the upper part and lower part of the gnathometer was made to be less than 15mm in height to ensure that the patients were relaxed and able to loosen their muscles before testing (Fernandes et al., 2003). If the design of the gnathometer was made to be more than 15mm, it would have caused a change in closing muscles that would result in the discomfort of patients and less accurate results. The smart gnathometer was designed using CAD software CATIA V5 and printed using a 3D printer (ENDER 3 PRO). The smart gnathometer was developed using a strong and light setting infill of 80% to guarantee that the device would not fracture during the test. It also had been designed with a slot for placing the force sensor to ensure the sensor would not come loose or dislodged during the test. The other improvement of the device was the occlusal platform was made 1mm in depth to allow a firm grip for the front teeth, which would ensure that the teeth would not move during the test. Furthermore, this prototype was developed to test the bite force at the back of the patient's mouth where a special design of slot was prepared for different test location of the jaw. A slot of standard size of jaw teeth were designed on the upper and lower part of the gnathometer.

Figures 1(b) and 1(c) illustrate the dimensions which had been applied to improve the prototype of the gnathometer.

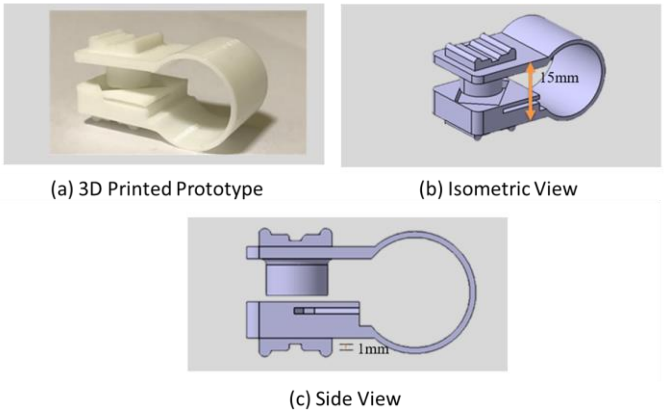


Fig. 1 (a) The gnathometer was fabricated from an Ender 3 Pro printer using PLA material. The infill was set up to 80% to increase the strength of the device, (b) 15mm gap between upper part and lower part and (c) 1mm depth at the teeth position platform. The design of the gnathometer was modelled using CATIA V5.

The connection of electronic parts

Various force sensors have been created to measure the force as pressure is applied on it, such as those made by Peratech QTCTM, Interlink Electronic FSR and Tekscan Flexiforce. In this study, a Flexiforce A301 from Tekscan Inc. from the USA was used as one of the parameters to measure the force of the device. It had a 9.53mm sensing area diameter with a thickness of 0.203mm and a length of 25.4mm, which were suitable characteristics for measurement of the bite force. The force sensor was inserted in the slot which had been designed at the gnathometer device. To represent the output of the bite force, the gnathometer devices were connected to an Android smartphone wirelessly using a Bluetooth module of HC6 that had been attached with an Arduino Nano microcontroller, as shown in Figure 2(a). Figure 2(b) shows the details of the electronic connection of the Arduino Nano. Arduino is an inexpensive microcontroller which can be easily programmed to create devices that can interact simultaneously with actuators and sensors. This microcontroller was built with an 8-bit ADC that could be programmed easily with Arduino IDE using C++ programming and had a total of 14 digital I/O pins with multifunction's such as input, PWM and power jack.

In comparison, a new type of developing microcontroller from SparkFun Electronics®, called SparkFun ESP32 Thing, was used to measure the maximum bite force, as shown in Figure 3(a). Figure 3(b) shows the details of the electronic connection of SparkFun ESP32 Thing. This microcontroller was built with 12-bit ADC with a 2.4 GHz WI-FI and Bluetooth combo chip and had a total of 32 multifunctional pins.

A software or an application was designed and made using the MIT AI2 Companion App inventor system, which would display the results of force and the voltage of the battery. Figure 4(b) shows the display of the application using the MIT AI2 Companion App inventor system. A voltage divider using two different values of resistor also had been attached to the microcontroller to measure and to get the respective voltages of the battery used. All electronic devices were placed in a designed box that was fabricated by 3D printing with PLA material. The box will protect the electronic devices from water splashing and high forces damages, as shown in Figure 4(a). The gnathometer developed in this study consist of 7 components:

1. Arduino Nano microcontroller and SPARKFUN ESP32 Thing
2. 3D printed gnathometer
3. 3D printed electronic system cover
4. FlexiForce A301
5. HC-06 Bluetooth module
6. 7.4V LiPo battery and 3.7V LiPo battery
7. An Android smartphone

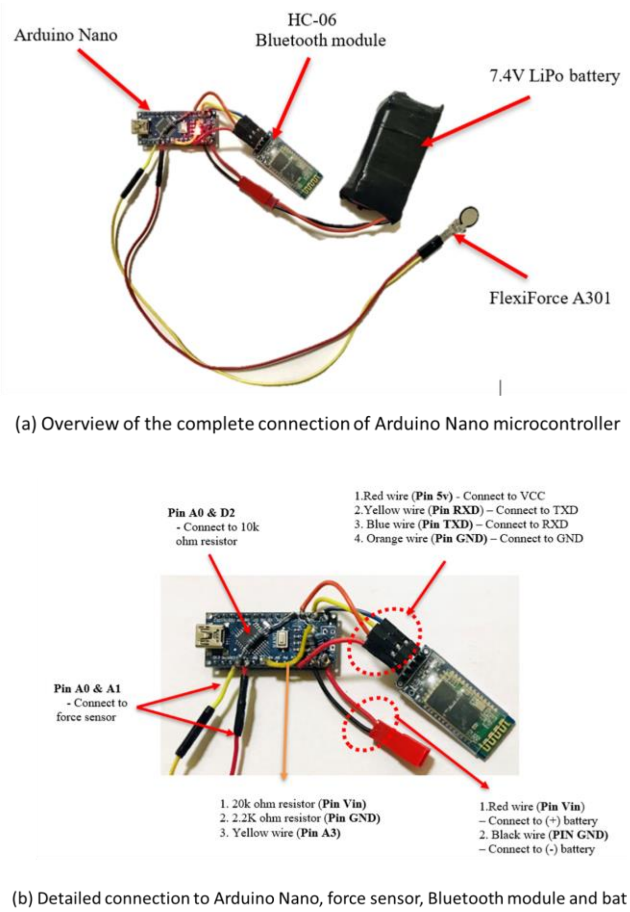
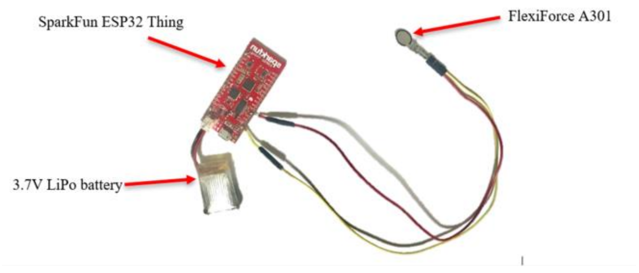


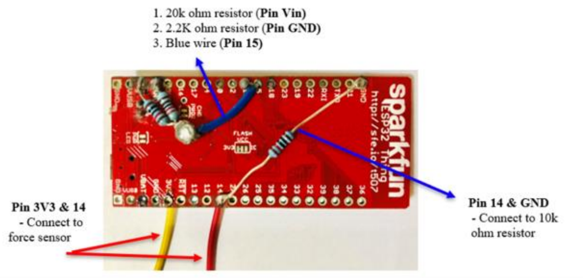
Fig. 2 (a) The complete arrangement of the electronic component using the Arduino Nano microcontroller. The main parts consist of Arduino Nano, HC-06 Bluetooth module, 7.4V LiPo battery and FlexiForce A301, (b) Details of the electronic connection show each pinout on the Arduino Nano microcontroller used to connect to electronic components

Force Sensor Calibration

Calibration of sensors such as force sensors, temperature sensors and ultrasonic sensors must be conducted prior to a clinical test on patients. This procedure has been used in many investigational studies to ensure accuracy and reliability of the device and the method. Reluctance to do this calibration test may result in inaccurate and unreliable results. Before to the calibration test, the sensor was conditioned five times for several seconds by placing weights on the force sensor to ensure that the sensor was in the active state (Parmar et al., 2017). In the calibration test, the force sensor was then inserted into the slot of the gnathometer before the test was carried out. Different authors have used different materials for the calibration test,



(a) Overview of complete connection of SparkFun ESP32 Thing microcontroller



(b) Detailed connection to SparkFun ESP32 Thing microcontroller, force sensor, built-in Bluetooth module and battery

Fig. 3 (a) The complete arrangement of the electronic component using SparkFun ESP32 Thing microcontroller. The main parts consist of SparkFun ESP32 Thing, 3.7V LiPo battery and FlexiForce A301, (b) Details of the electronic connection which show each pinout on the SparkFun ESP32 Thing microcontroller used to connect to electronic components.

such as magnets or two thin aluminium plates between the force sensors to prevent the sensors from being damaged (Takagi et al., 2009). Figure 5 showed the correct ways to measure the bite force of patients. As a safety precaution to prevent the saliva of patients from having direct contact with the wires, the force sensor and wires were wrapped with electrical insulation tape. Two sets of calibration tests were carried out to get the maximum accuracy and precision. The procedure steps for the first calibration test as follows:

1. A weight of 1.25 kilograms was put on the bite gauge of the gnathometer and was left on it for some time. After that, the output was recorded, and the weight removed.
2. A weight of 1.5 kilograms was put on the bite gauge of the gnathometer and was left on it for some time. After that, the output was recorded, and the weight removed.
3. A weight of 2.0 kilograms was put on the bite gauge of the gnathometer and was left on it for some time. After that, the output was recorded, and the weight removed.
4. Steps 1-3 were repeated using the weight of 3.25 kilograms, 3.5 kilograms and 4.75 kilograms.

For the second calibration test, each weight was placed on the Flexiforce A301 for five cycles several times, as shown in Figure 6. This method was carried out to get average output results to be more reliable and accurate. To analyse the accuracy error of the output voltage, a mathematical calculation has been carried out based on Equation 1.

$$Accuracy\ error = \frac{100(P_e - P_a)}{P_e} \quad (1)$$

(a) Gnathometer and controller box (b) Dashboard monitoring in Android apps platform

Fig. 4 (a) The complete arrangement of the 3D print component with an electronic system. The 3D printed electronic system cover was set to 20% infill while the gnathometer was set to 80% infill which had been adjusted using Ultimaker Cura 4.8, (b) The display on the smartphone application was developed using the MIT AI2 Companion App inventor system after being connected via Bluetooth. It displays the Bluetooth connection functions, force and voltage output values, as well as the UiTM logo.

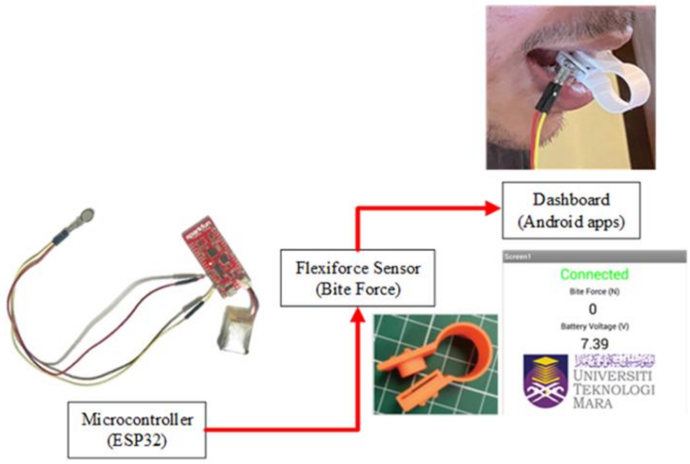


Fig. 5 The procedure to analyse the value of bite force of a denture patient. First, the patient will sit on a chair in a relaxed position. Next, the denture patient will bite on the designated place on the gnathometer. The FlexiForce A301 will detect the bite force and data will be transmitted to the smartphone via Bluetooth connection.

Where P_e is the experimental force as the pressure was applied on the force sensor and P_a is the corresponding or actual force of the weights. The value of accuracy error will be positive when the experimental force output is lower than the actual force and negative when the experimental force output is higher than the actual force. The accuracy of the output voltage can be calculated based on Equation 2, where the accuracy error was deducted from 100%.

$$Accuracy = 100 - |Accuracy\ error| \quad (2)$$

The calibration procedure had also been carried out in this calibration test to obtain more reliable results. In calibration, the protocol determines whether the force and voltage output have the presence of drift or not. Drift was generally known to be present when there was a slight change in output value after the intervals. This test was conducted by comparing the force and voltage output with the range of time. A gap of 30 seconds for all loads was applied or not applied in between using five repetitions for each weight, as shown in Figure 10. A mathematical calculation was done using Equations 3 and 4 to calculate the drift pressure and drift voltage in percentage value.

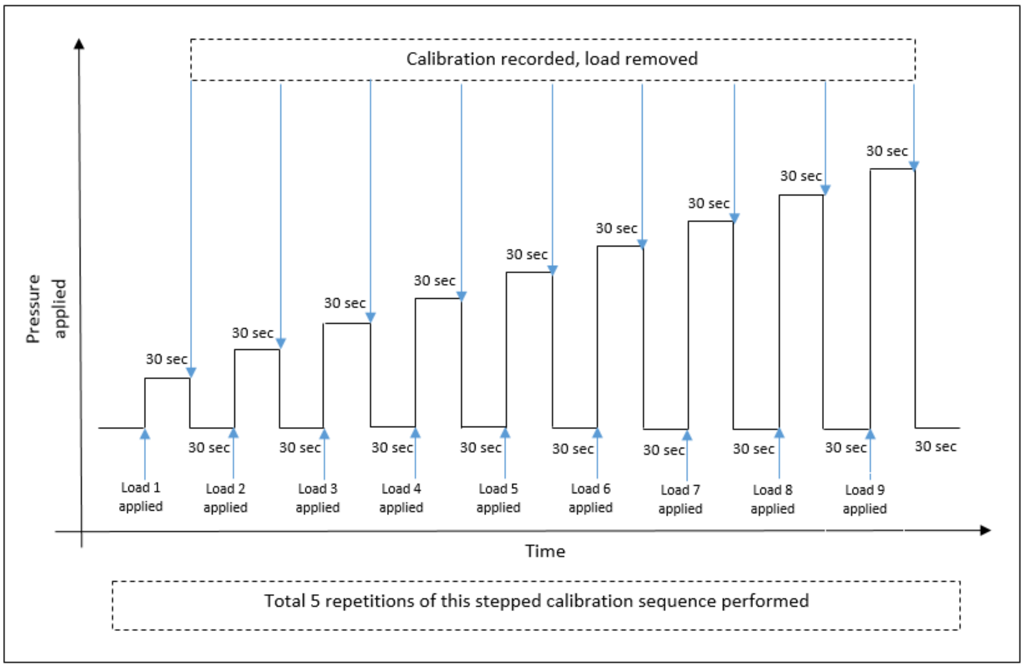


Fig. 6 The calibration cycle of five repetitions of force measurement. Each time interval was set up to 30 seconds for the load applied and at rest position in between. A stairs graph should be observed over time versus pressure applied.

$$Drift\ pressure = \frac{100(F_f - F_i)}{F_i} \quad (3)$$

$$Drift\ voltage = \frac{100(V_f - V_i)}{V_i} \quad (4)$$

Where F_i and V_i are the initial force and initial voltage respectively at the first moment where the value was in a steady state while F_f and V_f are the final force and final voltage respectively at the final moment where the pressure was applied at the end of a range of time. A constant value of the first weight was taken, which was 12.26N, and the initial time of 30 seconds was for force and voltage to be steady so that the drift values could be calculated. For static measurements, drift was taken for about 1 min, 3min, 5 min, 10 min and 15 min from when the pressure was applied (Fujii, 2006).

Error analysis is a necessary procedure to study the uncertainty that occurs during measurement. As this study was dependent on the measurement to extract the results, it was important to evaluate the uncertainties and to keep them as small as possible. Often the uncertainties are important but can be allowed for instinctively and without explicit consideration. For some measurements on apparatus with scales, uncertainty can come in many aspects, such as the large width of the scale markings on the instrument where users cannot determine the correct points on the scale marking to take the measurement. These small values indicate that the measurement will be as accurate as possible. Generally, the result of any measurement of quantity *x* is shown in Equation 5.

$$Measure\ value\ of\ x = x_{best} \pm \delta_x \quad (5)$$

Where x_{best} is the best estimate value of the measurement and δ_x is known as the error or uncertainty in the measurement of *x*. When the uncertainty δ_x is defined as positive, the $x_{best} + \delta_x$ will be the highest value of measurement and the $x_{best} - \delta_x$ will be the lowest value of measurement. For this study, the uncertainty of forces which had been decided and estimated was with tolerance of 1 Newton, and for voltage, it was with tolerance of 0.01 V when the measurements were taken.

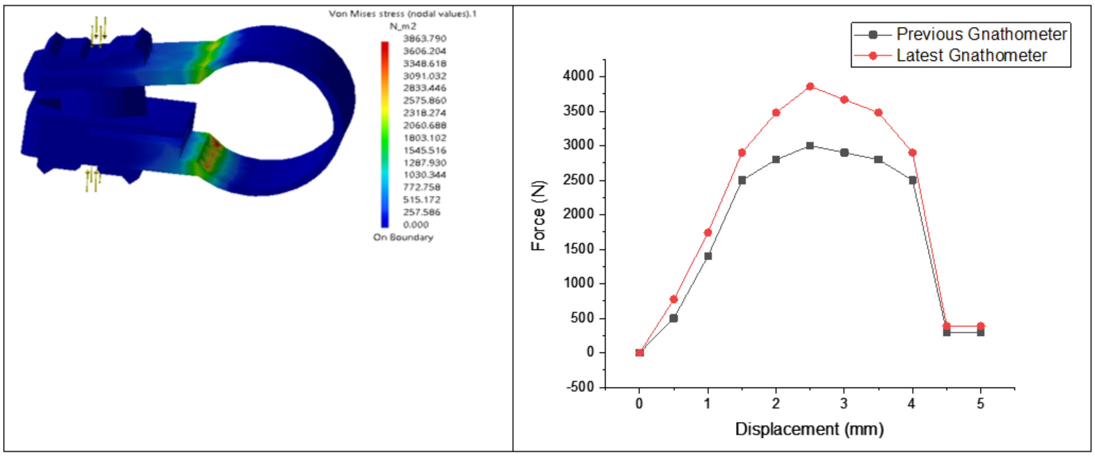
RESULT AND DISCUSSION

Static analysis of gnathometer

Static analysis is an advanced approach to calculate the device's strength without using proper laboratory procedures. In the finite element study, Von Mises stress analysis was carried out on the gnathometer device. Von Mises stress is a stress value to determine whether the given material would yield or fracture at specific points. Von Mises stress yield criterion states that when the stress is equal to or greater than the fracture limit of the same use of material, the device will fracture (Rohjoni et al., 2020). The static analysis study was carried out using CATIA V5 to implement polylactic acid plastic material and a load of 150N, as shown in Figure 7(a). Figure 7(b) demonstrates the gnathometer's yield strength for the studied gnathometer and the previously developed gnathometer

Table 1 - The drift force (in %) for the time taken of one to fifteen minutes of 12.26N with 30 seconds used to ensure that the values were in a steady state.

Time (min)	Initial Force (N)	Final Force (N)	Drift Force (%)
1	12.00	11.00	8.15
3	12.00	13.00	6.80
5	12.00	12.00	0.00
10	12.00	12.00	0.00
15	12.00	12.00	0.00



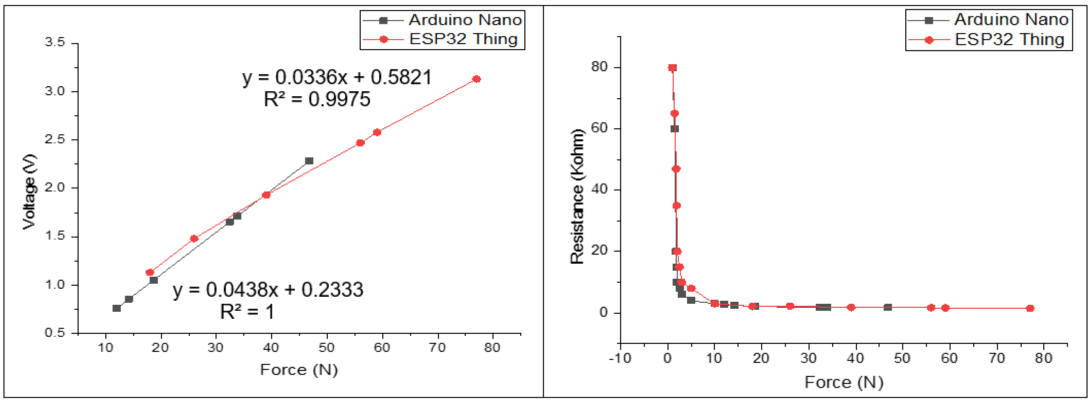
(a) The Von Mises stress of the gnathometer (b) Relationship between output force and displacement

Fig. 7 (a) The Von Mises stress of the gnathometer device was analyze using CATIA V5 software. The maximum stress from this analysis was 3863.790 N/m2, and it was located at the end of the large curve section. The material used for this test was plastic but with the implementation of PLA material properties of Young Modulus, Poisson Ratio, Density, Thermal Expansion and Yield Strength. (b) A relation between the displacement (in millimetre) from 1mm to 5mm and force output (in Newtons) for the studied gnathometer and previous gnathometer. The maximum force for the latest gnathometer was 3863.790 N, which was higher than for the previous gnathometer, which was 3000N, and then both gradually decreased as the gnathometer fractured.

Calibration Test

This section illustrated the results obtained from the calibration test for the force sensor connecting with the Arduino Nano microcontroller. The accuracy and the reliability of the force sensors used to test the bite force were confirmed during this calibration test. The first set of calibration tests analysed the impact of force with voltage and resistance. In Figure 8(a), there is a clear trend of a linear relationship between the output force sensor's average from 12N to 46.8N and voltage. A non-linear relationship between an average of five outputs of force sensor readings in Newton and resistance in K ohm has been shown in Figure 8(b). Compared to the actual data, a total of 5 cycle output readings of the force in Newton had been plotted against the actual force from a range of 12.26N to 46.60N in a histogram bar chart, as shown in Figure 9.

Force sensor drift is the steady deterioration of the sensor and accompanying components, culminating in results which differ from the calibrated condition. The drift of the force sensor occurred when there was a change at the output values of force



(a) Linear correlation between the force output (in Newtons) and voltage output (in Volts)

(b) Relationship between the force output (in Newtons) and resistance (in kilo ohms)

Fig. 8 (a) The positive linear correlation between the force output (in Newtons) and voltage output (in Volts) for Arduino Nano and SparkFun ESP32 Thing. As the force output increased, the voltage output also increased. For Arduino Nano, the maximum voltage output was 2.28V when the force output was 46.8N, and the maximum voltage output was 3.13V when the force output was 77.0N., (b) The relationship between the force output (in Newtons) and resistance (in kilo ohms) for Arduino Nano and SparkFun ESP32 Thing. For both microcontrollers, the resistance value decreased drastically from 1N to 10N and slowly dropped until it reached a steady value.

Table 1 The drift voltage (in %) for the time taken of one to fifteen minutes of 0.76V with 30 seconds used to ensure that the values were in a steady state.

Time (min)	Initial voltage (V)	Final voltage (V)	Drift Voltage (%)
1	0.76	0.75	1.33
3	0.76	0.75	1.33
5	0.76	0.76	0.00
10	0.76	0.75	0.00
15	0.76	0.76	0.00

Table 2 The value of average force, standard deviation, accuracy and accuracy error of force measurement.

Force (N)	Average Force (N)	Standard Deviation	Accuracy Error (%)	Accuracy (%)
12.26	12.0	0.71	-2.14	97.86
14.72	14.2	0.45	-3.50	96.50
19.62	18.6	0.55	-5.20	94.80
31.88	32.4	1.14	1.62	98.38
34.23	33.8	1.10	-1.24	98.76
46.60	46.8	0.84	0.43	99.57

in several amounts of time after the force was applied (Parmar et al., 2017; Velásquez et al., 2019). Table 1 shows the drift force results in Newtons during the calibration test after being calculated using Equation 3. Table 2 shows the results of drift voltage in Newtons which occurred during the calibration test after been calculated using Equation 4. To obtain more reliable and accurate results, the time used to calculate the drift force was from 1 minute to 15 minutes. Figure 10 (a) summarized the relationship between the time interval of 30 seconds and the force output. This study did not focus more on the force itself, but the voltage was also considered to reduce the drift. A stepped graph of time with an interval of 30 seconds against voltage was plotted as shown in Figure 10(b) to see whether there was a drift occurring during the voltage output which had been extracted. Accuracy of force sensor output is defined as how close the measured force values recorded is to the actual value of force in Newtons. The values of standard deviation, accuracy and accuracy error have been presented in percentage (%) as shown in Table 3.

This study aimed to integrate a smart wireless gnathometer with electronic circuits and mechanical elements presented as more compact and user-friendly for of all group ages. There have been many improvements made through this study, especially in terms of mechanical design and electronic systems. Previous studies have shown issues and challenges in developing smaller, compact, user-friendly, less hazardous, and cost-effective devices. Some of the devices which have been developed were lacked in accuracy and precision, thus did not meet the standard requirements to be used clinically for bite force measurement with the modern and advanced technology in this new era, researchers have generated ideas to improve gnathometer devices. This study has successfully developed a novel gnathometer device using a Fused Deposition Modelling (FDM) machine of a 3D printer. By using in-house fabrication, using the ENDER 3 PRO 3D printer, the gnathometer were produced quickly and better. 3D printing is a method of creating a physical object from a three-dimensional digital model by depositing numerous thin layers of a material.

Polylactic acid (PLA) was selected as a material for fabrication of the gnathometer rather than Acrylonitrile butadiene styrene (ABS) due to its superior mechanical and biocompatible properties. PLA material is stronger and stiffer than ABS material. Most importantly, PLA material is safer to use than ABS as it is less toxic. Furthermore, the use of a 3D printer can reduce the cost of reproducing the gnathometer devices. For example, the cost of producing a smart gnathometer device is less than a T-Scan system from the financial point of view due to its material used and its advanced technology. This gnathometer can be easily set up by clinician and patients themselves with the help of a manual that would be provided as it is just a simple setup between mechanical and electronic systems. As the gnathometer devices were set up with 80% infill with a dynamic quality of 0.16mm in Ultimaker Cura 4.8.0, it can withstand high-pressure forces beyond maximum human bite force. In the static finite element analysis study, the

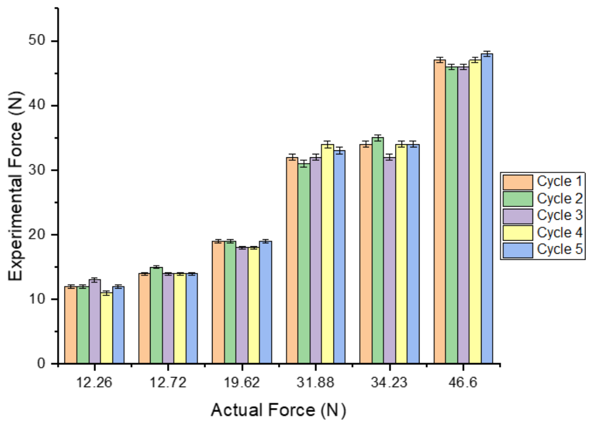
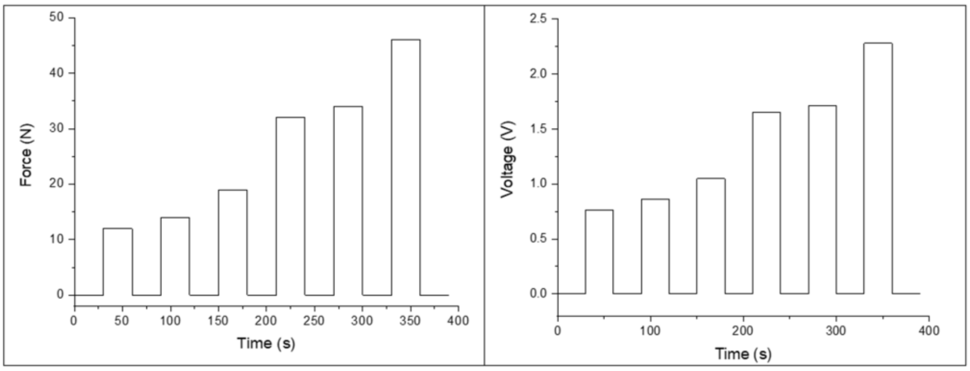


Fig. 9 The histogram bar chart results with error bar between the Actual Force (in Newtons) and Experimental Force (in Newtons). Each weight from 12.26N to 46.6N was taken five times to get reliable results. From the bar chart, the average reading for each weight has been indicated.



(a) Stepped graph of time against force (b) Stepped graph of time against voltage

Fig. 10 (a) A stepped graph of time (in seconds) against force (in Newtons). Each weight output was taken five times for every 30 seconds and the sensor was rested for 30 seconds between the applications of weight, (b) A stepped graph of time (in seconds) against voltage (in Volts). A stepped graph of time (in seconds) against force (in Newtons). Each weight output was taken five times for every 30 seconds and the sensor was rested for 30 seconds between the applications of weight.

maximum Von Mises stress of the gnathometer device was reported to be 3863.790 N/m2 with the maximum stress located at the end of the large curve of the gnathometer. The present study showed that the new gnathometer had better strength than the previous study on the old gnathometer, which can withstand a 3000 N/m2.

The selection of a cost friendly and multifunctional microcontroller that acts as the brain of the device was a wise choice. It is a powerful tool which can connect wirelessly with smartphones and computers with the help of C++ coding programming in Arduino IDE through Bluetooth or WI-FI. Comparing the features of Arduino Nano and SparkFun Esp32 Thing, the esp32 microcontroller must be in-built with Wi-Fi and Bluetooth. It can directly charge the LIPO battery without any external connection. In terms of the calibration of the force sensor, it cannot be proven yet as to which microcontroller is better. The MIT AI2 Companion App inventor system is an advanced step where people can easily create a simple application. This application can read and show many sensor values such as temperature, force and voltage in smartphones. This application is compatible and can connect smartphones wirelessly with the microcontroller board using Bluetooth, WI-FI or Bluetooth Low Energy (BLE).

The calibration test conducted for this study showed that the Flexiforce A301 from Tekscan Inc. of the USA can be successfully calibrated with the data according to given parameters. This type of force sensor is also suitable for testing the maximum bite force of humans as it can accurately measure the force data output up to 445N. The size of this sensor is smaller than the previous force sensor using Flexiforce A201. This shorter version of sensor would be very convenient to all patients as the force sensor would not touch the cheeks of patients when the selected teeth in the jaw are tested. Many positive feedbacks received from patients for this improved design of the gnathometer.

From the calibration results, we could observe that the force in Newtons was directly proportional to the voltage during the pressure applied. The value of force output using Arduino Nano

Table 4 Comparison between the current study with the six previous studies of gnathometer devices in terms of materials used and types of sensors used.

Product	Material used	Sensors Type	References
Smart Gnathometer	Polylactid acid (PLA)	FlexiForce A301	Current Study
Bite Force Recorder	Acrylonitrile butadiene styrene (ABS)	FlexiForce A201	(Roffie et al., 2020)
Gnathodynamometer	Metallic part with plastic biting pad	No sensor used (Manual force scale)	(Ortug, 2002)
T-Scan System	Not stated	Custom built-in force sensor	(Nalini and Sinha, 2018)
Stainless Steel Gnathometer (Manual force scale)	Stainless steel with rubber biting pad	No sensor used	(Psillakis et al., 2004)
Disposable Gnathometer	Not stated	No sensor used (Manual force scale)	(Baat et al., 2007)
Housed Transducers	External silicon layer with an internal hard plastic layer	FlexiForce A201	(Testa et al., 2016)

microcontroller was more reliable and more accurate to the actual force compared to SparkFun ESP32 Thing. The outcomes of this study also demonstrated that when the force was applied to the force sensor, the resistance of the circuit would gradually decrease. These results matched those findings observed in earlier studies. The most interesting findings were that there would be no drift when the sensor was calibrated for more than 5 minutes. There are several possible explanations for the drift to occur when calibrated for less than five minutes. It may have been related to vibration during the calibration, the condition of sensors during the test, whether well prepared or parts of the sensors may have been damaged. From the calculation of accuracy and accuracy error, we observed that the accuracy was in a higher state, which was more than 94.80%, and the accuracy error was less than 5.20 %. This accuracy error occurred due to the natural drift, shock and vibrations, and overpressure during the calibration test. For the drift which occurred during the study, most sensors would have this drift during the test. So, the method to control the drift is by calibrating the force sensor but it is difficult to remove 100% of the drift.

In this study, the research objective had been carried out successfully to integrate a smart wireless gnathometer with electronic circuits and mechanical elements. The new developed device was more compact, safe to use, affordable in price and easily accessible by users. This study also examined the bite force using the developed gnathometer to achieve improvement with more accurate and precise results as well as being a more user-friendly instrument for clinical use. This newly developed gnathometer was inexpensive from the financial point of view as the method of fabrication utilized a 3D printer using Polylactic acid (PLA) filament. The device had been developed with consideration of previous research in terms of drawbacks in mechanical and electronic systems.

A calibration test was conducted where known weights were put onto the gnathometer. The Flexiforce A301 was inserted at the slot part of the gnathometer device. This test was carried out to clarify the accuracy and the drift presence between experimental force output and actual force values. The findings have shown that the force output is directly proportional to the voltage output. The second significant finding was that the resistance value would gradually decrease as the force output increases until it reaches the minimum point and steady state. The results of force output are reliable as the accuracy of the experimental force and actual force is a minimum of 94.80%, which was expectedly high, and with an accuracy error of 5.20%, which was expectedly low.

CONCLUSION

This research has extended our knowledge of the crucial aspects which will be used in the dental field in measuring the bite force of patients. It can predict and improve the longevity and success of treatment provided to patients thus will be able to anticipate and avoid any failure related to excessive or uneven distribution of occlusal force in the jaw. This study also allows other researchers to improve the methods in measuring the bite force and investigate on other factors affecting the maximum bite force. Future research to improve the gnathometer mechanism by integrating mechanical elements such as ratchets, and bearings may be possible. It may contribute more comfort to patients as the device would allow for a 360 degrees rotation where the sensor and wires would not touch patients. Additionally, researchers can figure out more advanced ways in the dental industry to use the Internet of Things (IoT) technology embedded in the system for a real-time bite force monitoring.

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