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Development of a Wear Testing Machine for Dental Crown Application

Panya Aroonjarattham*, Chakrit Suvanjumrat and Ekachai Chaichanasiri

ABSTRACT

A three axes wear testing machine for a dental crown was developed for human tooth application. There were two main sections of the controllers: the application of an AC servomotor (Z-axis) for creating and controlling the force which is used in testing and the application of a step motor (X-axis and Y-axis) for creating and controlling the motion. This study aimed to compare the ability of the controlling force of the AC servomotor on two different surfaces—a smooth flat surface and a dental crown surface. Three testing cases were considered at frequencies of 0.5, 0.75, and 1 Hz in a range of motion of 1 mm: 1) simulating the force of chewing (0–60 N) and the motion of a circular process, 2) simulating a constant force (60 N) of one way movement in a circular process and 3) simulating a constant force (60 N) of the reciprocating movement in a circular process. The machine was tested using a dental crown, which was made of zirconia, by simulating the force, the motion and the various conditions of the teeth in the oral cavity. The force which occurred in all three axes was measured by the load cell.

According to the experiment, the AC servomotor was able to control the force exerted on two different surfaces with nearly similar results. The average force errors on the smooth surface and the dental crown surface were 13.70 and 13.82%, respectively. The *root mean square errors* of the smooth surface and the dental crown surface were 17.47 and 16.99, respectively.

Keywords: Dental crown; wear testing machine; AC servomotor; pin on flat; zirconia.

INTRODUCTION

Wear is the damage of material surfaces from the friction of two objects. The process of wear is complex and has a variety of components that occur simultaneously, depending on the environment considered. The wear of material relates to lubrication and friction of the surface, hardness, roughness and the types of wear.

The damage to a human tooth can be considered from many determinants such as usage, weakness over time and by accidents that may occur. The restorative material should have the same or better capability than the natural human tooth material. The surface of a tooth under friction force from mastication and biting conditions loses thickness of only 10–40 μm per year (Ramalho and Antunes, 2007). A dental crown is a fixed device which is used to cover damaged teeth. It also protect and strengthen the natural teeth as shown in Figure 1. The crown material may be made of gold, porcelain, porcelain-fused-to-metal, resin, ceramic and other alloys (Carazola-Burch and Burch, 2011).

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All kinds of dental crowns are tested under operating conditions. Therefore, the wear testing of the crown under the expected conditions of use is necessary. Many *in vitro* testing devices have been designed and are used in various tests. The main purpose is to mimic the oral cavity condition and they can be divided into three groups: scratch test, two-body wear test and three-body wear test as shown in Figure 2.

This study aimed to develop a three-axis wear testing machine for dental crowns. The machine was designed to mimic the chemical and mechanical systems experienced under real human oral cavity conditions. The machine simulated the human chewing force using an AC servomotor, the motion of the human jaw and a cavity that reflected the oral human-like pH conditions and temperature to test the wear of new kinds of dental crown material.

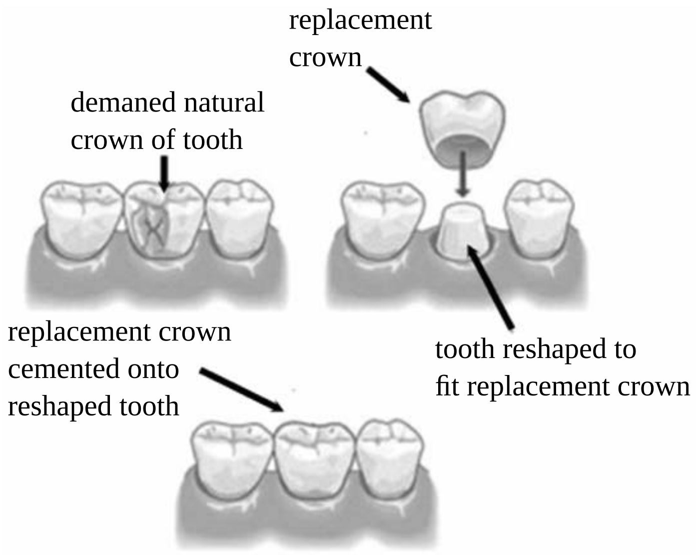

Figure 1 Replacement crown on a damaged tooth (34th Street Dental Care, 2012)

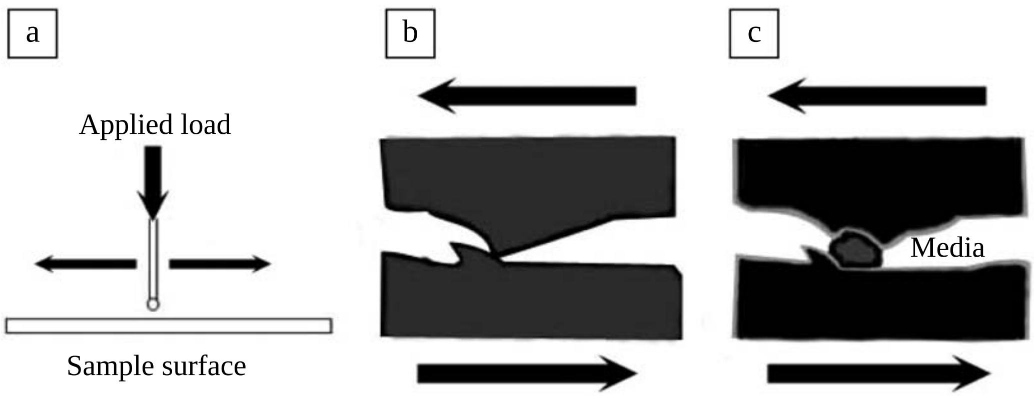

Figure 2 Three types of wear test: (a) Scratch test, (b) Two-body test and (c) Three-body test (arrows show the applied load).

MATERIALS AND MEDTHODS

The testing machine which was developed could simulate movement during the chewing process in an oral cavity for the purpose of studying the wear resistance of a dental crown. The machine could be used in tests on cyclic loading, where the forces were varied or constant (Figure 3). The loading was controlled by an AC Servo Motor Driver (model MSDA203A1A; Panasonic Corp.; Osaka, Japan).

The wear testing machine is shown in Figure 4. The components of this machine are divided into two parts: the upper part that is used to control the force applied by the AC motor and the bottom part which is used to control the motion of the step motor. All of these parts are controlled by a microcontroller and the force applied is measured by load cells which are mounted on each axis.

During the test, in the Z axis, the AC motor works alternatively between the position control mode and the torque control mode. The position mode works on the vertical movement of the ball screw on the stylus—a part made up of stainless steel in shape of a 1 mm diameter, rounded end that contacts the sample material in the container box. Then the machine is switched to the torque mode. The user adjusts the force so that it is constant for the standard test or cycling

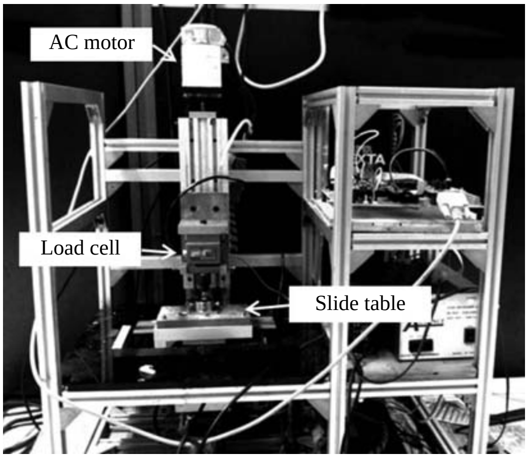

Figure 4 Wear testing machine.

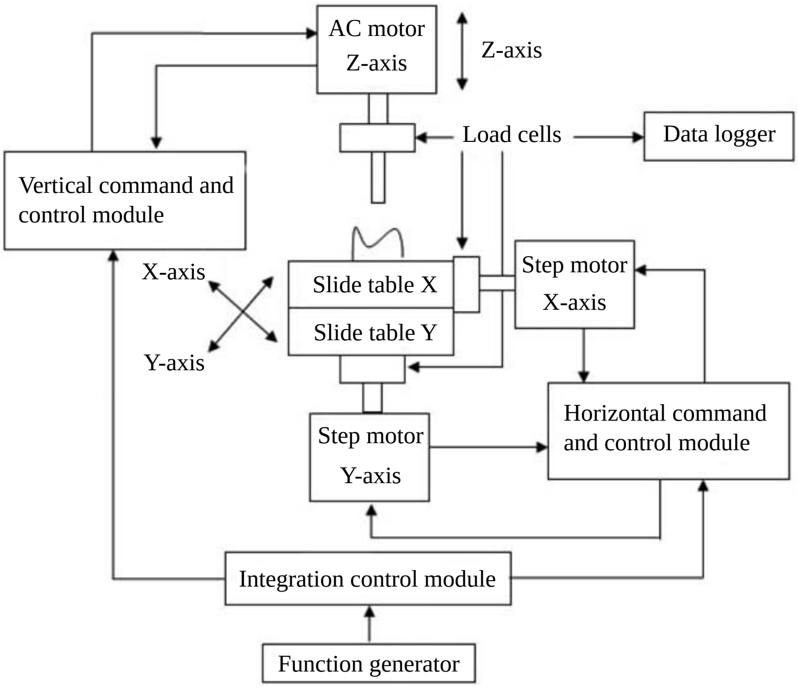

Figure 3 Design layout of the test machine.

mode. The process simulates the chewing force by controlling the load on the stylus, using a half sine curve cycle.

The plate is placed on the X-Y slide table which moves in two directions. The testing material is held on a flat plate which is exchangeable for different testing samples. The movement in the X axis is driven by a step motor through a ball screw mechanism and its velocity is used to adjust the frequency and distance of the oscillation by a pulse signal from the controller. The movement on the Y axis changes the position on the material. The controlling system of Y axis is similar to that of the X axis. A thermal unit and water are also applied in the wear testing. The pump is equipped with a heater, controlled by a temperature control, which is connected to the container, in order to circulate water at a constant temperature of 35 ^{o}C. The pump injects water into the crown surface to control the testing material's temperature and acts as artificial human saliva. The wasted water is drained out as non-reusable water to prevent any confusing effect from the abrasive particles in the testing material.

Testing observed the results of a force which was controlled by the AC servomotor between the two different materials of the dental crown and the flat surfaces. In each mode, cycling frequencies of 0.5, 0.75 and 1 Hz were tested, respectively. This experiment was divided into three testing cases:

1. A one-way chewing force was conducted on two different surfaces: flat and the dental crown surface. It was generated as an unstable force in a positive half sine curve which had a maximum force at 60 N to simulate the movement of the human mastication system.

2. A one-way constant force between samples which had different surface properties was conducted by inputting force in a normal wear test. A 60 N force was applied throughout the test and the movement was undertaken in a loop.

3. A two-way constant force was studied through different surface properties, using force in the normal wear test. A force of 60 N was applied throughout the test. The movement was done in a back-and-forth motion according to the standard of ASTM 133-95 (American Society for Testing and Materials, 2010).

The moving paths of the three cases on the two difference surfaces are shown in Figure 5.

The testing machine applied an unstable force (chewing force) and constant loading at frequencies of 0.5, 0.75, and 1 Hz. The loading had a maximum value of 60 N, a stroke length of 1 mm and 50 cycles for testing. The conditions for all experiments are shown in Table 1.

RESULTS

The test was divided into three cases: modes 1, 2, and 3 and cycling frequencies of 0.5, 0.75, and 1 Hz were tested, respectively. During the tests, the force was controlled by a controller, based on the principle of a sine curve, in order to simulate the force occurring in the human masticatory system. The equation used was Force = 0.0022 × Number of bits -1.1082; R^2 = 0.9993. This equation can be programmed into a microcontroller to control and generate the force via the AC servomotor. Moreover, a straight-line equation or constant force was used for the wear test according to the standard of ASTM G133-95 (American Society for Testing and Materials, 2010). The result from the test showed the force generated on all three axes by inputting a force on two types of samples: a smooth-surface and an actual tooth-surface sample.

Case study 1: One-way chewing force

Case study 1 was a test conducted on two different properties (flat and dental crown). It generated an unstable force in the positive half of the sine curve having a maximum force at 60 N to simulate the movement of the human masticatory system. The distance of masticatory movement was 1 mm at various frequencies (0.5, 0.75, and 1 Hz). A data logger was used to record information to study the effect on dental crown materials of the force created from the AC servomotor on the flat surface.

The resultant forces per cycle from the data logger were calculated to find an average value for 50 cycles at frequencies of 0.5, 0.75 and 1 Hz, respectively. Furthermore, the results were compared with the equation created from the micro controller in case study 1 (Figure 6).

Case Study 2: Constant force-one way

This case study tested samples which had different surface properties by inputting force in a normal wear test. A force of 60 N was applied throughout the test and the movement was one way. The movement distance in the test was 1 mm at various frequencies of 0.5, 0.75, and 1 Hz. A data logger was used to study the effect on the dental crown materials of the force created from the AC servomotor on the smooth surface.

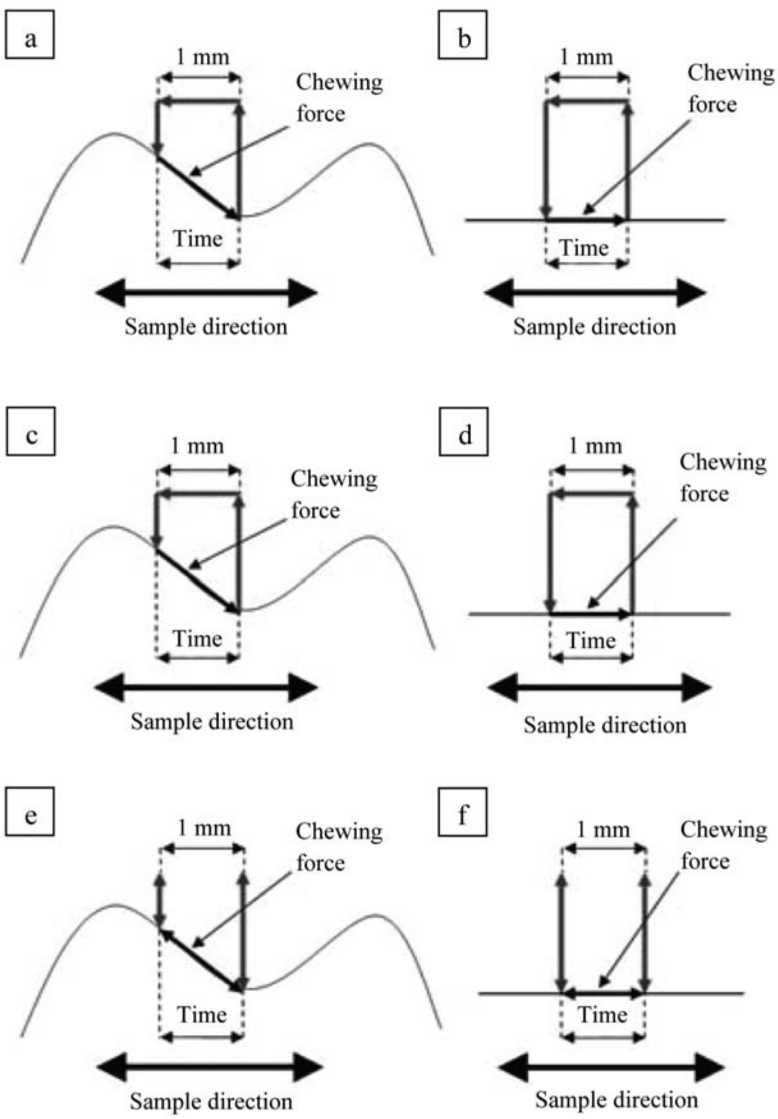

Figure 5 Moving path in the tests: (a) One-way chewing force on crown, (b) One-way chewing force on flat, (c) Constant force one way on crown, (d) Constant force one way on flat, (e) Constant force two ways on crown and (f) Constant force two ways on flat.

The results per cycle from the data logger were calculated to determine the average value for 50 cycles at frequencies of 0.5, 0.75 and 1 Hz, respectively. Furthermore, the results were compared with the equation created from the micro controller in case study 2 (Figure 7).

Case Study 3: Constant reciprocating force

This case study considered different surface properties by inputting force in a normal wear test. A force of 60 N was applied throughout the test with movement in a back-and-forth motion according to the standard of ASTM G133-95 (American Society for Testing and Materials, 2010). The distance in the test was 10 mm at various frequencies of 0.5, 0.75 and 1 Hz. A data logger was used to study the effect on dental crown materials against the force created from the AC servomotor on a smooth-surface subject.

The results from the data logger were calculated to find the average of 50 cycles at frequencies of 0.5, 0.75 and 1 Hz, respectively. Furthermore, the results were compared with the equation created from micro controller in case study 3 (Figure 8).

DISCUSSION

Many attempts have been made to replicate the load and movement of the mastication system (DeLong and Douglas, 1991; Sajewicz and Kulesza, 2007). However, this is a difficult task, as there are many parameters that need to be controlled. Force measurements were recorded by load cells, which were placed in each axis which resulted in many possible methods to model the cavity system. The machine developed for this study applied an AC servomotor to control the loading to be as close as possible to the human chewing process. The shape of the loading curve was similar to the positive half sine curve wave (DeLong and Douglas, 1991; Hu *et al*., 1999;

Table 1 Machine conditions for testing.

Case	Frequency (Hz)	Surface	Distance (mm)	Force (N)	Recorded number of points	Number of cycles
One-way	0.50	Crown	1	0–60	100	50
chewing	0.50	Flat	1	0–60	67	50
force	0.75	Crown	1	0–60	50	50
	0.75	Flat	1	0–60	100	50
	1.00	Crown	1	0–60	67	50
	1.00	Flat	1	0–60	50	50
Constant	0.50	Crown	1	60	100	50
force	0.50	Flat	1	60	67	50
one way	0.75	Crown	1	60	50	50
	0.75	Flat	1	60	100	50
	1.00	Crown	1	60	67	50
	1.00	Flat	1	60	50	50
Constant	0.50	Crown	1	60	100	50
force	0.50	Flat	1	60	67	50
two ways	0.75	Crown	1	60	50	50
	0.75	Flat	1	60	100	50
	1.00	Crown	1	60	67	50
	1.00	Flat	1	60	50	50

Heintze, 2006; Zhou and Zheng, 2008) with constant force control. An AC servomotor was chosen as it was very stable, responsive and easily controllable. This resulted in accurate control of loading; moreover, the AC servomotor had torque control for controlling the vertical loading that made it simple to use. In this experiment, the loading was chosen from a range of 0 to 60 N, which was similar to the mastication loading of the human chewing process (Heintze, 2006) and it controlled the constant force to 60 N to test the wear according to the ASTM G133-95 standard (American Society for Testing and Materials, 2010). Forces were generated on different surfaces—a flat surface according to American Society for Testing and Materials (2010) and the

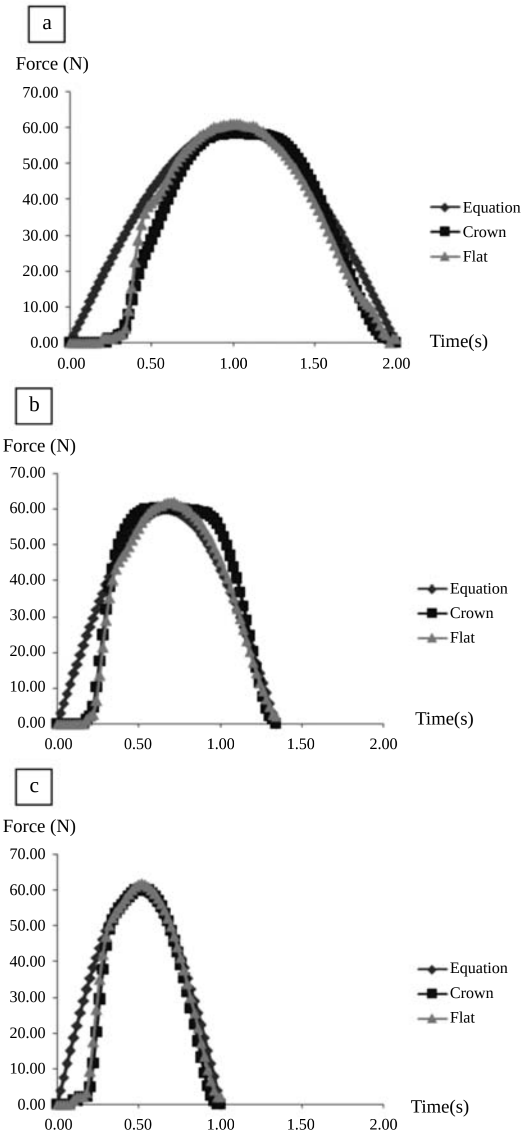

Figure 6 Comparison of graphs of flat plate and dental crown with equation in case study 1 at frequencies of: (a) 0.5 Hz, (b) 0.75 Hz and (c) 1 Hz.

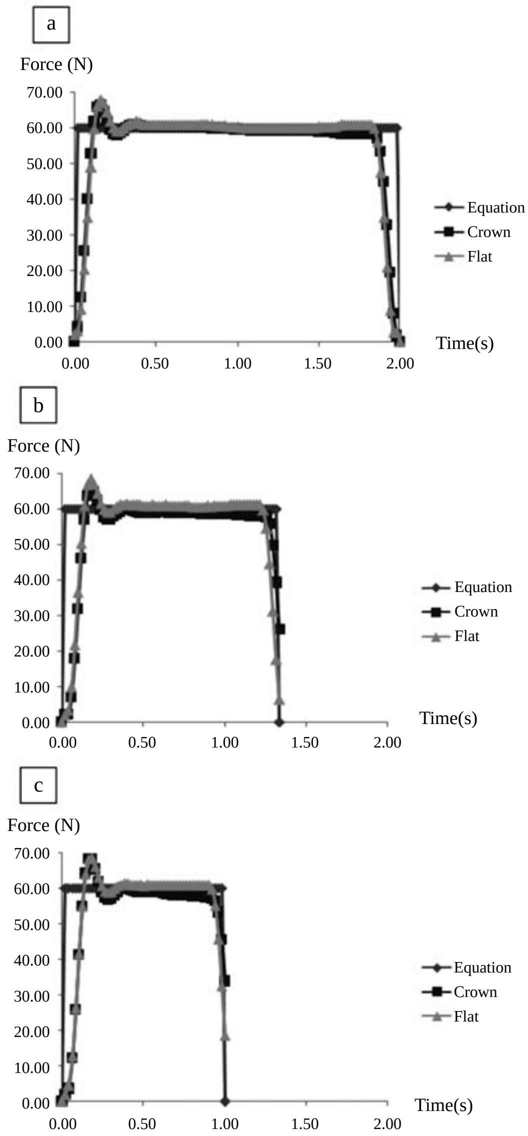

Figure 7 Comparison of graphs of flat plate and dental crown with equation in case study 2 at frequencies of: (a) 0.5 Hz, (b) 0.75 Hz and (c) 1 Hz.

rough surface of a dental crown resembling a tooth in the oral cavity.

Creation of chewing force

The creation of a chewing force in this experiment utilized the positive half sine curve equation—namely, Force = 0.0022 × Number of bits - 1.1082; R^2 = 0.9993. This simulated force was similar to the human chewing force but did not include standard testing of wear as before. Therefore, the simulated force only simulated wear in the cavity. If carefully analyzed, the force, caused by chewing, might be approximated by other forms of equation such as a parabola. The force measured from this research was based on many factors such as race and individual characteristics. However, this experiment applied a general approach because it was important to the study tooth properties and the development of dental materials used in making of dental crowns, including decreasing the cost of the building process and designing materials which were used to replace teeth. Subsequently, the tests in this section were based on specific decisions.

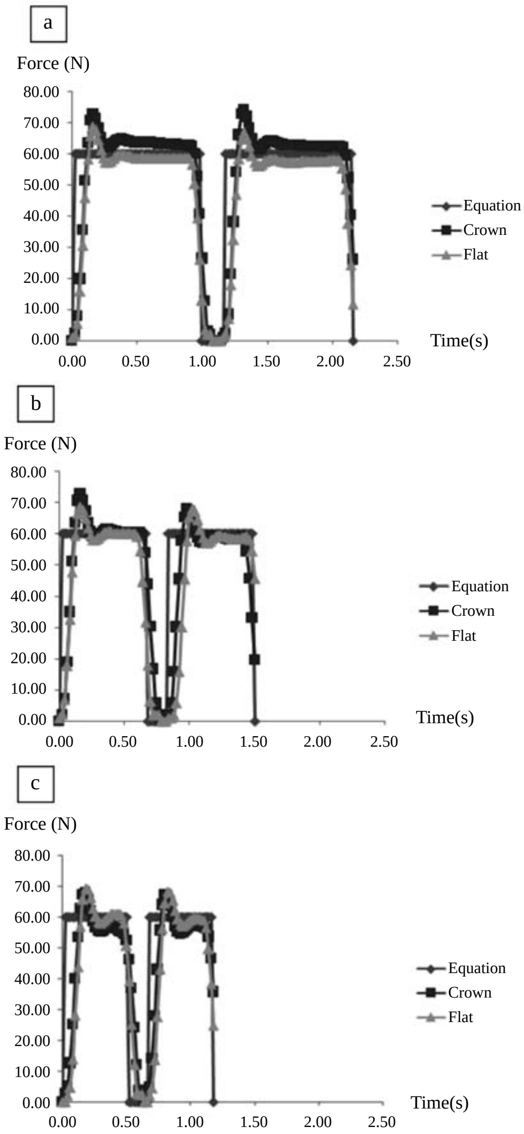

Figure 8 Comparison of graphs of flat plate and dental crown with equation in case study 3 at frequencies of: (a) 0.5 Hz, (b) 0.75 Hz and (c) 1 Hz.

Analysis of results of occurring force

The analysis indicated many factors that affected the error rates of the creating force. When analyzing the frequencies of motion, it was found that each test case produced error rates that increased with various frequencies and motion. Therefore, the frequencies of motion had little influence on the accuracy of the information but affected the errors of the information as well. The limitation of the force measurement confined the, higher frequencies and led to higher error rates of the measured force. Errors were inherent in the microcontroller as well because the microcontroller controlling this machine used PIC18F247J11, which managed contact with the outer devices better than other controllers; there were many functions used to control the hardware but compared to other kinds of microcontrollers (AVR and ARM), the velocity in calculating or processing was inferior. Therefore, there is a chance that it resulted in slow processing in the main controller of the control system which may have caused a delay in sending the results and data while testing, which in turn may have led to a slow response by the machine. Another important factor that caused errors in the system was the mechanical system, which included various components such as the ball screw and slide rail which were used in installing the load cell. These devices imposed a low friction force. In this experiment, a lack of smoothness may have occurred because of the friction generated in the decreased force through the ball screw. Each part of the axis might have produced unequal friction through the axis because it was operated with different lubrication. In the experiment, the load cell was placed on a slide rail to reduce the loading caused by other axes which produced greater accuracy in the axis of slide rail. This slide might have caused reduced smoothness during the experiment as may have the ball screw, which may have affected the resulting force measured in this experiment.

The force control by the AC servomotor in the torque control mode determines the velocity of motor rotation. Thus, the velocity of the motor would affect the response of the motor; the quick rotation speed required a greater force. This demonstrated the efficiency of the force control from the motor. However, the study showed that a higher motor speed could cause higher rates due to an overshoot in the controlling system. This was clearly shown in cases 2 and 3. Therefore, the velocity in this test was slightly low at 300 rpm, resulting in a lower error rate due to the reduced over shoot, so that it did not have much effect on the response of the system. At the beginning of the test, the stylus did not touch the testing surface so there was a space between the stylus and the testing material. The motor generated a zero force for approximately 0.2 s at the beginning of the test which resulted in the various different forces causing high error rates. If a faster speed were used, it would generate more overshoot as mentioned above which in turn would result in higher error rates as well. An increase in the velocity might have some impact because the quick motion would make the stylus hit the testing material at the beginning of the test. This study of the wear mechanism did not consider impact in the test because this may have affected errors greatly. Therefore, the reason for choosing the high error rates that occurred at the beginning of the test due to the low speed of motor was to avoid the impact caused by the quick start.

In this research, the test machine was operated under three different cases at frequencies of 0.5, 0.75 and 1 Hz and a testing distance of 1 mm to obtain various error rates of force. Flat and dental crown surfaces were wear tested using the AC servomotor with the ball screw controlling the applied force during the test. The results of the measured force were similar to the equation that was used for creating the force in the controller. Moreover, the results of the occurring force on the flat and dental crown surfaces very similar.

In this experiment, the number of analog signals, which was controlled by the microcontroller, would affect the increasing accuracy of the force rates, depending on the frequencies of signaling by the microcontroller. If the microcontroller were highly efficient in controlling the signal, the force error rates would decrease. In this test, the frequencies of the signal were 120 Hz due to the limitation of the microcontroller. To deliver a more accurate force control rate, the microcontroller would require replacement with one with a more efficient evaluating process. The results of the three different cases are shown in Tables 2, 3 and 4 for case studies 1, 2 and 3, respectively.

Microstructure

A scanning electron microscope was used to scan the test samples on the surface of a zirconian dental crown which was coated with porcelain. After the wear test was performed with the developed machine, a fracture on the tested surfaces was found. The powder particles on the tested surfaces were found at the 5,000 cycles as a result of wear on the porcelain layer which was used to coat the dental crown on the zirconia. When the number of cycles was increased to 10,000 and 12,000 the surfaces after the test were similar with fractures and small round particles present, which were similar to the zirconia with scattering on the tested surfaces as shown in Figure 9 showing that the wear of the dental crown went all the way down to the layer of zirconia.

When considering the fracturing that occurred on surfaces after testing, it was found that the width and the length of the fracture was very similar to the testing stylus (1 mm) and the testing distance (1 mm) which showed that the testing distance control of the machine developed in the study was highly precise in controlling the testing distance.

American Society for Testing and Materials standard test

Analysis of the average error rates in the developed testing machine for each point of 50 cycles and a comparison of them to the error rates according to ASTM G133-95 (American Society

Table 2 Average force errors and root mean square errors of case study 1 with three frequencies.

Sample	0.5 Hz		0.75 Hz		1 Hz	
	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)
Dental crown surface	32.69	9.83	29.63	9.28	34.49	11.15
Flat surface	29.30	8.62	23.87	8.68	29.09	9.76

Table 3 Average force errors and root mean square errors of case study 2 with three frequencies.

Sample	0.5 Hz		0.75 Hz		1 Hz	
	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)
Dental crown surface	7.59	12.58	8.43	14.20	9.64	15.38
Flat surface	10.11	14.04	11.18	14.53	11.10	15.16

Table 4 Average force errors and root mean square errors of case study 3 with three frequencies.

Sample	0.5 Hz		0.75 Hz		1 Hz	
	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)	Average force error (%)	Root mean square error (N)
Dental crown surface	12.33	13.75	14.13	17.44	20.31	16.69
Flat surface	12.71	14.44	13.54	17.71	20.55	21.42

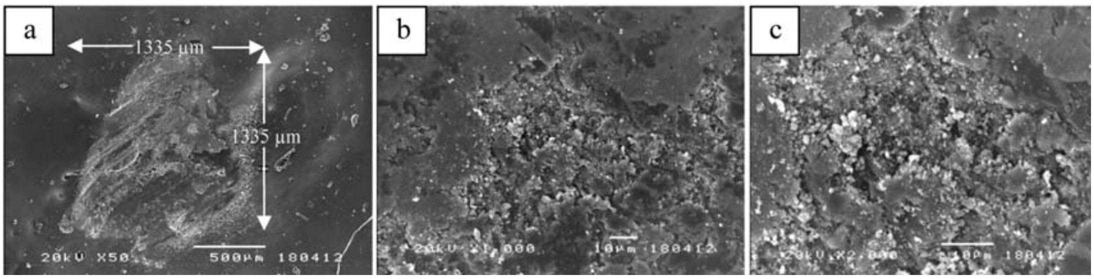

Figure 9 Scanning electron micrographs of dental crown surfaces after the wear test using the test machine with 10,000 cycles: (a) at 50×, (b) at 1,000× and (c) at 2,000×.

for Testing and Materials, 2010) found that the average error rates in this experiment (occurring during the period of the controlling force) was 2.23% which was slightly more than the standard rate of 2%. This may have been a result of the limitations and various problems that took place during the testing process.

The developed machine was designed to move on three axes; therefore it was capable of applying wear testing according to other ASTM standards (American Society for Testing and Materials, 2010) by modifying the program which was used for controlling the movement in the lower part of the machine. For example, this machine could be applied to pin-on-flat sliding wear to study the effect of hardness in various areas on the teeth or other materials, to determine when to replace the teeth because the strength rates of various parts of the teeth are different. It could be concluded that the machine developed could test all surface areas of teeth, with different hardness levels, because the process does not fix the position through the control system. Moreover, this machine could be further developed because it is not necessary to change the hardware of the machine when the software is improved.

CONCLUSION

The adaptation of an AC servomotor to control the load in a wear testing machine for dental crowns was efficient and created few additional forces in the loading tests on the surface of a dental crown. Furthermore, the machine was capable of simulating the load associated with normal tooth operation in the oral cavity. The performance of the testing machine feature is shown in Table 5.

The two horizontal axis movements could be adapted to create many testing patterns, including loading measurement in all axes. In this study, the effect of the loading of testing materials can be controlled using various frequencies from 0.1 to 1 Hz depending on the test. The machine was able to simulate various conditions of the human cavity by controlling the temperature of lubricants. The test was divided into three different situations and the effect on the flat surface and the dental crown was rather similar.

Table 5 Properties of the wear testing machines

Motion	Three axes
Type to test	Ball on flat, pin on flat and flat on flat
Frequency (Hz)	0.1–1.5
Loading (N)	0–200
Load pattern	Constant loading and half sine loading
Range of motion (mm)	0–2
Temperature (^{o}C)	30–80

The average error rates over all cases were 13.70% of the crown surface and 13.82% of the flat surface. Thus, this wear testing machine for dental crowns has practical application in the future in order to test other synthetic materials in dental crowns. Moreover, it can be used to test real tooth surfaces without having to make the materials into a smooth flat surface. It is useful in the study and development of the properties of materials which can be used to replace human teeth.

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