Effect of Axial Bruxism Bite Force on Titanium Alloys Biomaterials Experimental Chewing Test and 3D Finite Element Simulation

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Research Article

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Abstract

Bruxism can be defined as the process of direct contact with teeth and dental materials with an involuntary jaw-tightening movement. In this process, teeth and dental materials can be exposed to various damage mechanisms. This study aims to analyze the wear behavior of cp-Ti, Ti-5Zr, and Ti-5Ta alloys, which are frequently preferred as dental materials in the human body, under different Bruxism wear processes by experimental in vitro chewing cycle and finite element analysis simulation method. Cp-Ti and titanium alloy test specimens with cylindrical geometry were exposed to a direct every-contact wear mechanism for 30 seconds under 100N bruxism chewing bite force. The bruxism chewing cycle continued for 300 minutes at a frequency of 1.8 Hz. Microanalysis of the wear surfaces of the samples after the experimental study was carried out with Scanning Electron Microscopy(SEM). The Bruxism wear volume loss that occurred in the wear area of the test specimens was measured with a 3D non-contact profilometer. The results obtained within the scope of this study showed that the Bruxism wear resistance increased by adding zirconium and tantalum to pure titanium material. In axial Bruxism bite forces, the least wear volume loss occurred at 90° bite forces chewing process. However, in the Finite Element Analysis simulation, it was observed that the maximum stress area was evident in the implant structure at 75° bite force chewing process. This will make it difficult for the implant to osseointegration within the body and will cause various damage mechanisms to the integrity of the implant.

1. Introduction

Titanium material is preferred as a biomaterial due to its important behavior in living tissue. In addition, a more optimum material selection can be made by obtaining new material behaviors with titanium alloys. It is reported in the literature that titanium alloys are preferred as biomaterials due to their high mechanical (such as high high strength-to-weight ratio, good fatigue resistance, relatively low Young's modulus, good biocompatibility), and chemical behavior [1]. However, biomaterials placed in the human body can be exposed to various wear mechanisms. It has been reported in the literature that titanium and its alloys do not have sufficient wear resistance [2]. The element zirconium is in the same group as the element titanium in the periodic table. It is known that zirconium and titanium elements show similar chemical behavior [3]. It is also a known fact that the element zirconium reduces the fusion temperature in titanium alloys [4]. Zirconium also contributes to the α and β isomorphic properties of titanium alloy and causes solid solution hardening of titanium alloys [5]. It is also known that pure zirconium element has superior biocompatibility and corrosion resistance [4, 6]. Due to the superior mechanical and chemical behavior of the zirconium element, efforts have been made to obtain new biomaterial alloys by adding them to titanium alloys in recent years. Various complex wear mechanisms can occur in different parts of the human body. Bruxism can cause teeth and dental materials to be exposed to various damage mechanisms. It can significantly increase the effect of the wear mechanism due to the continuity of the contact surface of the reciprocal materials and the excess of the bite force in the tooth-tightening process. Concerning bruxism, it is important to distinguish between sleep bruxism and awake bruxism. In the literature, sleep bruxism can be defined as rhythmic or non-rhythmic chewing muscle activity of an
individual during sleep, and this condition is not considered a movement disorder [7]. On the other hand, bruxism in the awake state can be defined as a mechanism of repetitive and prolonged contact between the teeth randomly creating pressure on the lower jaw. This situation is not considered as a movement disorder in individuals [7]. Dental contact is not a dominant activity during a 24-hour cycle. It is estimated that tooth contact occurs for approximately 17.5 minutes in 24 hours; Muscle activity-related sleep bruxism [8], lasts for approximately 8 minutes during a full sleep time, which is usually between 7 and 9 hours [9]. It has been reported that the incidence of bruxism is %6- %20 in the adult population and %20 in the clenching type, and it is predominantly seen in women [9]. Most theories adhere to multifactorial etiology and distinguish between environmental factors (anatomy, dental occlusion, receptor input), central (central nervous system), and psychological factors [8]. Bruxism is generally thought to be the main contributing factor to tooth wear, periodontal disease, and temporomandibular joint disorders [10].

The duration of the chewing cycle ranges from 0.7 to 2 seconds, and the contact time is between 0.2 and 0.3 seconds. It has been observed that the occlusal force during clenching is as high as 520–800 N. The duration of Bruxism attacks varies between 2 and 375 seconds [11]. Optimizing the experimental conditions in the laboratory environment of the parameters in clinical studies is important for the stability of the in vitro chewing /bruxism test simulation results. Analysis of the wear behavior of biomaterials placed in the living body is of great importance in determining the life of the material. For this reason, many test devices have been designed in the literature that can perform wear analysis of biomaterials in a laboratory environment [12–19]. However, it is important for the validity of the test results that the designed test devices can simultaneously apply the active parameters on living tissue to the test material. In addition, evaluating the in vitro experimental study results with the finite element analysis (FEA) simulation method will increase the validity of the test method. Therefore, in this study, experimental study results were obtained and the Bruxism chewing test process was simulated with the finite element analysis (FEA) method.

2. Material and Method

2.1 In vitro Bruxism Chewing Simulation

In this study, a computer-controlled device with rotating parts that can determine the abrasion resistance of biomaterials placed in the human mouth has been designed and manufactured in an experimental study. The periodic wear behavior of biomaterials placed in the human mouth was determined by the experiments carried out on this device The characteristics of the Bruxism chewing movement throughout the experiment were transferred to the computer environment as real-time data via the USB 3.0 port. The schematic representation of the computer-controlled Bruxism wear device, Fig. 1 (drawn with the CATIA V6 3D Software program). The samples used in this study were prepared in cylindrical form (12 mm diameter 2 mm thickness) from each test group (cp-Ti, Ti-5Zr, and Ti-5Ta (in wt. %)). The test samples were commercially produced from Ti, Zr, and Ta sections with about 99% purity in sheet form. These test samples were previously tested in chewing tests in a different study [20]. Within the scope of this study, Bruxism chewing tests were performed in an area outside the wear area. To carry out metallographic
examinations of pure titanium and its alloys, some of the samples were split with a water-cooled low-speed diamond saw (Isomet Buehler GmbH, Duesseldorf, Germany), and microstructure analyses were performed. Pure titanium and titanium alloy test specimens with cylindrical geometry were exposed to a direct contact wear mechanism for 30 seconds under 100 N axial Bruxism chewing bite force. The bruxism chewing cycle continued for 300 minutes at a frequency of 1.8 Hz. In this process, the bite force remained constant and the lower jaw provided a sliding movement of 0.7 mm through the bruxism test period. Aluminum oxide (Al₂O₃) balls with a diameter of 6 mm were used as abrasive material for each Bruxism rotating chewing test procedure. The wear volume loss of pure titanium and titanium alloy materials was determined by a non-contact 3D profilometer after the Bruxism chewing test procedures. In addition, microanalysis of the wear surfaces of the test specimens after the experimental study was carried out with Scanning Electron Microscopy(SEM). In this study, 37°C distilled water sprayed on the wear surface of the test sample allowed the particles that broke off during wear to be separated from the surface. Thus, direct contact wear (two-body wear) for Bruxism process conditions is carried out through chewing tests. In addition, the temperature occurring during the contact of the counter material and the test sample was adjusted back to body temperature. This reduced the effect of thermal cycling effect on Bruxism wear through the chewing test process. Because in vitro wear experiments, to see the effect of the active parameter on the test sample accurately and consistently, it will be possible to remove the inactive parameters from the system.

2.2 Finite Element Analysis Bruxism Chewing Simulation

In this study, bruxism test modeling of dental material was carried out using the ANSYS 19 workbench academic version program. For this reason, the mesh amount is set to a maximum of 30,000 which this ratio is in a range of values sufficient for the analysis performed Bruxism chewing test analyses. The material was chosen as a titanium alloy from the general material library of the ANSYS program. The mechanical properties of the selected titanium alloy material and modeling test specimen are shown in Fig. 2. The values in this figure represent the ideal mechanical properties of the material. Bruxism bite force loading of 100 N and a sliding motion of 0.7 mm were determined under in vitro experimental conditions. In the modeling, a force of 100 N was applied perpendicular to the test sample (in the -z direction). For the test specimen to move in the horizontal axis, the rotary motion of the test specimen was provided at a frequency of 1.8 Hz by using a wear coefficient of 1 N (in the x direction). The wear coefficient varies according to the material's surface behavior. However, in this study, pure titanium material was considered to be under optimum conditions. Figure 3 shows the finite element analysis modeling steps of the titanium test material by considering the experimental environment parameters. (a: counter body simulation fixed support, b: rotating lateral motion starting point, c: rotating lateral motion process, d: Bruxism bite force starting point e: Bruxism bite force process, and f: simultaneous application of all test conditions to the test pure titanium specimen) It is an inevitable fact that loads during chewing will create stress on the parts that make up the implant material. In this study, pure titanium and titanium alloys tested were designed for implant integrity, and the effect of the Bruxism
chewing process on implant integrity was analyzed. Thus, the changes in the integrity and structure of
the implant placed in the mouth during the Bruxism chewing process were analyzed for all axial Bruxism
bite forces. Figure 4 shows the implant structure designed from titanium material according to standard
dimensions.

3. Results

The surface hardness and wear volume loss occurring after different axial bruxism chewing tests of pure
titanium and titanium alloys tested within the scope of this study are shown in Fig. 5. While Ti-5Zr
titanium alloy has the highest surface hardness value, pure titanium and Ti-5Ta have similar surface
hardness values. The maximum volume loss occurred at 90° Bruxism bite force for pure-titanium, while
the least volume loss occurred at 75° Bruxism bite force for Ti-5Zr through the chewing test process. The
results obtained within the scope of this study showed that the Bruxism wear resistance increased by
adding zirconium and tantalum to pure titanium material for all Bruxism chewing test procedures. XRD
analyses of the materials tested in this study are shown in Fig. 6. The cp-Ti contained the \( \alpha \) phase, while
the Ti-5Zr and Ti-5Ta contained \( \alpha, \alpha', \alpha'' \) and \( \beta \) phases. Figure 7 shows an example of the Bruxism impact
wear surface analysis after the Bruxism chewing wear test. When Fig. 7 is examined, it is seen that the
first step effect wear area occurs during the Bruxism impact movement this wear area can be defined as
where permanent plastic deformation occurs under the effect of Bruxism bite force. It is estimated that
the wear depth of this area changes with the Bruxism bite force. The second step can be considered as
completing the Bruxism lateral movement of the lower jaw. With this movement, particles broken off from
the Bruxism impact area will be carried on the wear surface during lateral movement. It is estimated that
the wear area distance of this area changes with the Bruxism lateral movement. The last step can be
defined as the completion of a Bruxism chewing cycle by separating the upper jaw from the lower jaw.
The purpose of choosing a 3D non-contact profilometer is to analyze the wear particles broken off from
the surface. The particles broken off from the wear surface of the pure titanium test material were less
evident than the other alloys. This situation can be defined as the alloying elements added to titanium
alloys contributing to different stress formations during the wear process and separating from the wear
surface. Figure 8 and Fig. 9 show the Finite Element Analysis results of the implant structure in chewing
test experiments under 90° and 75° Bruxism bite forces for one chewing cycle respectively. (A: (Applying
bite force to Bruxism, B: Normal Stress Analysis, C: Shear Elastic Strain, and D: Max Total Deformation
Analysis). In this analysis method firstly, 75° and 90° Bruxism bite force was applied to the designed
implant structure through the chewing test process. The implant body is fixed in a screw structure in a
way that it can behave within the acrylic resin structure (Fig. 8A and Fig. 9A). Then, Finite Element normal
stress analysis was performed on the implant structure through the chewing cycle process. It was
observed that the applied biting force could remain in the optimal working zone on the test material and
homogeneous normal stress distribution was observed in the implant body structure. (Fig. 8B and Fig.
9B). While the implant body showed homogeneous shear strain behavior under 90° Bruxism bite force
(Fig. 8c), distinct shear strain regions were observed at 75° Bruxism bite force through the chewing test
process. Finally, while homogeneous max total deformation areas were formed at 90° Bruxism bite force
max total deformation areas increased in the direction of axial loading at 75° Bruxism bite force through the chewing test process (Fig. 9D). Figure 10 shows the wear surface micro and nano-structure of the tested cp-Ti and titanium alloys after the 90° Bruxism bite force chewing test process (A-C: Cp-Ti, D-F: Ti-5Zr and G-I: Ti5Ta). Different wear structures occurred in the Bruxism wear area of the cp-Ti test material (Fig. 10A). It is observed that particle transfer from the abrasive material (as antagonist material Al₂O₃) to the test material occurs during the bruxism chewing test process (Fig. 10B). These transported particles moved on the surface during the wear process and acted as a third body through the Bruxism chewing process. In addition, the Bruxism wear area of cp-Ti distinct cracks and gaps occurred at the nanoscale after the chewing test process (Fig. 10C). Ti-5Zr exhibited a more homogeneous Bruxism wear area behavior than Ti-5Ta and cp-Ti (Fig. 10D). Titanium alloys containing Zr and Ta particles along the direction of Bruxism wear lateral movement contributed to the better wear behavior of the test material through the Bruxism chewing test process (Fig. 10E and Fig. 10H). Nano-sized cracks were observed on the Bruxism wear surface of both alloy test materials (Fig. 10F and Fig. 10I).

4. Discussion

The researchers concentrated on laboratory in vitro test experiments because living tissue in vivo test experiments were very long, costly, and ethical problems [21–23]. Therefore, researchers develop in vitro laboratory experiments and finite element analysis computer simulations. However, the human body has a very complex and constantly changing structure. Therefore, it is very important that the experimental conditions applied in the laboratory environment can simulate parameters in living tissue. In this study, pure titanium test material was subjected to the Bruxism chewing test procedure to determine its mechanical and esthetic behaviors. Additionally, in vitro, Bruxism chewing test experimental parameters were simulated with the finite element method. The results obtained in this study showed that cp-Ti, Ti-5Zr, and Ti-5Ta biomaterials undergo various damage mechanisms in the mechanism of bruxism and that the axial bite force accumulated in a region can mathematically form the fracture mechanism. The intraoral tribological process has a continuous and complex structure due to the presence of living tissue and a wide axial movement ability through the chewing cycle process. In many studies in the literature, in vitro laboratory test mechanisms can model two and three-body wear mechanisms [18, 24] The parameters such as bite force, thermal cycle, third body medium, direct impact time, antagonist material that occurred during the chewing movement can affect the wear resistance of the test material. There is no fixed rule on the characteristics of abrasive material in the literature. For example, It is recommended to use enamel abrasive material in OHSU and ZURICH chewing simulation tests while other chewing simulation tests recommended to use steatite, aluminum oxide, stainless steel, alumina, and zirconia ceramic balls as abrasive materials [12–16]. Since enamel does not have a specific geometry and not every material will show the same mechanical and aesthetic properties, the validity of the results will decrease [13]. Therefore, using antagonist material with the same mechanical and aesthetic properties in all chewing tests will increase the validity of the results. In addition, the hardness, geometric shape, and size of the antagonist material are important due to the effect of wear on the contact surface. In this study, since the load distribution on the wear contact surface should be homogeneous, Al₂O₃ balls
(circular with a diameter of 6 mm) were used as the antagonist material in each chewing test. It is reported in the literature that ceramics with a diameter of 6 mm as an antagonist material can imitate human molars and have similar wear rates as enamel and composite materials [25–28]. In this study, standardization of in vitro experimental conditions was a factor that would increase the validity of the experimental results. While the highest surface hardness value was measured in the Ti-5Zr test sample, pure titanium, and Ti-5Zr showed similar surface hardness values (Fig. 5). This result shows that the Zr element provides hardness to the titanium alloy. It has been reported in the literature that the surface hardness value increases when the Zr element is added to titanium alloys [1]. In the literature, it has been reported that there is a linear relationship between surface hardness value and wear resistance [29, 30]. However, the results obtained in this study showed that there is no linear relationship between the hardness value of the test materials and their Bruxism wear resistance. A study in the literature reported that there is no relationship between the hardness and wear resistance of titanium and titanium alloys [4]. In another study in the literature, the hardness values of alloys in the range of Ti-10Zr and Ti-40Zr were examined, and it was concluded that the hardness value increased with the increase in the Zr ratio in the alloy [3]. In this study, the hardness of Ti-5Zr material was significantly higher than that of Ti-5Ta and pure titanium test materials. It is possible to say that martensitic microstructure and solid solution hardening contribute to the hardness of Ti-5Zr titanium alloy.

Wear analysis methods such as contact or non-contact profilometer devices, digital microscopes, optical sensors, and laser scanning are used to determine the volume loss of wear surfaces after chewing tests of biomaterials. In a study conducted in the literature, volume and vertical loss variables were evaluated using different methods such as profilometer, optical sensor, and laser scanning [31]. As a result, the wear characteristics of the impact area and lateral movement direction are important parameters for wear volume analysis. Figure 7 shows a 3D Bruxism wear characteristic example of the chewing cycle area using a non-contact 3D profilometer. It was observed that the particles were separated from the surface along the Bruxism wear area as we moved from the impact area to the lateral movement. This result shows that plastic deformations occur in the Bruxism wear area during the chewing movement. It has been observed that the stress distributions in the implant structure differ as the Bruxism bite force angle changes through the chewing cycle process (Fig. 8 and Fig. 9). While a homogeneous stress distribution occurred at 90° Bruxism bite force, it was observed that stress accumulation areas formed in 75° Bruxism bite force chewing tests. This result shows that axial Bruxism bite forces can make it difficult for the implant to osseointegration within the body and will cause various damage mechanisms to the integrity of the implant.

It has been reported in the literature that the chewing movement is completed in three cyclic steps: 1) initial occlusal contact, 2) sliding contact of tooth surfaces, and 3) separation [32]. The particle peaks formed in the wear area were separated from the surface when the Bruxism bite force started and was transported by the lateral movement of the lower jaw. This mechanism continued throughout the Bruxism chewing cycle, resulting in the occurrence of particle hills. Wear particle hills caused the erosion surface to turn into a rough structure. The surface roughness of metallic biomaterials can affect wear resistance. It is known that the rough surfaces of metallic biomaterials are more affected by the corrosion
environment than smooth surfaces [33]. The mechanical and aesthetic properties of the antagonist material are important parameters in vitro chewing cycle simulation tests because the mechanism of wear occurs between at least two opposing surfaces. It was observed that nano-cracks occurred on the Bruxism wear surface in the direction of lateral movement (Fig. 10C, F, and I). It has been reported in the literature that contact loading can create certain modes of crack initiation and propagation, such as radial-median cracks, edge cracks, and ring/cone cracks [32]. Nano-cracks occurring on the wear surface are a result of repetitive Bruxism biting force loading. These cracks may continue below the surface, which is an indication of fatigue wear. The particle peaks observed in this study were removed from the wear surface and transported by a Bruxism lateral movement mechanism in Fig. 10B, E and H. Bruxism will be an increasing factor in deformation mechanisms as the micro-cracks occurred during the lateral wear movement will enable the movement of aggressive fluid into the material in corrosive environments. However, in this study, the corrosive environment effect was excluded from the test parameters. In future studies, the effect of a corrosive environment on biomaterial wear areas can be investigated through the Bruxism chewing test process.

5. Conclusion

Biomaterials placed in the human body will inevitably be exposed to damage mechanisms in a continuous and complex structure. It will not always be possible to realize the mechanical, aesthetic, and chemical behaviors of biomaterials on living tissue due to reasons such as long time and high cost. Therefore, researchers develop in vitro laboratory experiments and finite element analysis computer simulations. However, these experimental methods must have the ability to simulate the parameters that occur in living tissue. In addition, evaluating the in vitro experimental study results with the finite element analysis simulation method will increase the validity of the test method. Therefore, in this study, experimental study results were obtained and the Bruxism chewing test process was simulated with the finite element analysis method. The results obtained within the scope of this study showed that the Bruxism wear resistance increased by adding zirconium and tantalum to pure titanium material. In axial Bruxism bite forces, the least wear volume loss occurred at 90° bite forces chewing process. However, in the Finite Element Analysis simulation, it was observed that the maximum stress area was evident in the implant structure at 75° bite force chewing process. This will make it difficult for the implant to osseointegration within the body and will cause various damage mechanisms to the integrity of the implant.

References


Figures
Figure 1

The schematic representation of the computer-controlled Bruxism wear device and in vitro test simulation.
Figure 2

The mechanical properties of the selected titanium alloy material and modeling test specimen

Figure 3

Finite element analysis modeling steps of the titanium test material by considering the experimental environment parameters. (a: counter body simulation fixed support, b: rotating lateral motion starting point, c: rotating lateral motion process, d: Bruxism bite force starting point e: Bruxism bite force process, and f: simultaneous application of all test conditions to the test pure titanium specimen)
Figure 4

Implant structure designed from titanium material according to standard dimensions

(a: Fixture, b: Fixture + Screw c: Abutment + Screw d: Implant)

Figure 5

A VICKER'S MICROHARDNESS (VHN)

B Mean Bruxism Wear Volume Loss mm³

![Graphs showing Vicker's Microhardness and Mean Bruxism Wear Volume Loss]
The surface hardness and wear volume loss occurring after different axial bruxism chewing tests

Figure 6

XRD analyzes of the materials tested in this study

Figure 7

Example of the Bruxism impact wear surface analysis after the Bruxism chewing wear test.
Figure 8

Finite Element Analysis results of the implant structure in chewing test experiments under 90° Bruxism bite forces for one chewing cycle. (A: Applying bite force to Bruxism, B: Normal Stress Analysis, C: Shear Elastic Strain and D: Max Total Deformation Analysis)
Figure 9

Finite Element Analysis results of the implant structure in chewing test experiments under 75° Bruxism bite forces for one chewing cycle. (A: Applying bite force to Bruxism, B: Normal Stress Analysis, C: Shear Elastic Strain and D: Max Total Deformation Analysis)
Figure 10

Wear surface micro and nano-structure of the tested cp-Ti and titanium alloys after the 90° Bruxism bite force chewing test process (A-C: Cp-Ti, D-F: Ti-5Zr and G-I: Ti5Ta).