ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article DOI: 10.5281/zenodo.15729095

# Dynamic thermal cycle ambient simulation under mouth motion; a finite element analysis

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**ABSTRACT**

The aim of this study is to analyze the experimentally established thermal cycle test experiment using the Finite Element Analysis (FEA) method. Within the scope of this study, the thermal-mechanical behavior of the pure titanium test material at minimum and maximum temperature environments was analyzed in the simulation environment occurred at 1/1 scale with the experimentally established parameters. Pure titanium test materials that different geometry were kept at 5°C temperature for 30 seconds and then exposed to 65°C environment during 2 seconds change period. Thus, 1 thermal cycle was completed under mouth motion simulation. The results obtained showed that the temperature distribution in the circular test sample exhibited a more homogeneous distribution behavior than the square test sample. This result reveals the importance of the geometric structure of the test sample in the experimental environment conditions. Therefore, the use of a circular test sample in *in vitro* laboratory thermal cycling experiments will increase the accuracy of the results obtained under mouth motion simulation tests. As a result, the results obtained in this study are expected to mathematically guide the selected parameters in *in vitro* and *in vivo* studies.

**Keywords:** Mouth motion thermal simulation, Biomaterials, Finite Element Analysis.

## INTRODUCTION

In recent years, titanium and titanium alloys have been preferred as biomaterials in the living body due to their superior mechanical and biocompatibility behavior. It has been reported in the literature that titanium alloys can be preferred in the treatment process due to their superior behavior such as high strength-to-weight ratio, good fatigue resistance, relatively low Young's modulus, good biocompatibility, and high corrosion resistance.[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] Finite Element Analysis remains an essential method for initial screening of biomaterial behavior. Thermal cycling is one of the most preferred test methods to simulate the life cycle of biomaterials implanted in the body.[3] In thermal cycle tests, the mechanical, aesthetic and chemical behaviors of biomaterials in the body can be predicted during the time they remain in the body. Researchers are trying to predict the mechanical behavior of biomaterials by using thermal cycling test experiments with *in vivo*, *in vitro* and finite element analysis testing simulation methods. These test methods may have many advantages and disadvantages compared to each other. For example, while the *in vivo* test method takes a very long time, the *in vitro* and finite element analysis test methods can be completed in shorter time periods. However, the ability to mimic living structures when creating test method mechanisms can significantly affect the accuracy and validity of test results. In the literature, many researchers have tried to determine the mechanical, chemical and aesthetic behaviors of biomaterials with *in vitro* wear and test methods and wear test mechanisms.[4–7] The concept of thermal cycling has been used effectively in the literature for approximately 70 years.[8] This process is basically based on the heating and cooling process of a material placed in the tooth or body throughout its life cycle.[8] The environment to which teeth and dental materials are exposed while biting into an ice cream after drinking a hot coffee can be given as an example on living tissue. This system has traditionally been used to simulate *in vivo* aging of restorative materials by subjecting them to repeated cyclic hot and cold temperatures in a water bath to reproduce the thermal changes that occur in the oral cavity.[8] In thermal cycling tests performed in the laboratory, it is very important to select minimum and maximum temperatures. Table 1 gives examples of the temperatures of the absorbed fluids and the resulting average minimum and maximum tooth surface temperatures.[9] This study evaluates the effect of temperature changes occurring in the human oral environment on sat titanium biomaterial with different geometries using the finite element analysis test method under mouth motion simulation. As a result, the results obtained in this study are expected to mathematically guide the selected parameters in *in vitro* and *in vivo* studies.

**Received** 26.11.2024
**Revised** 06.01.2025
**Accepted** 13.02.2025
**Publication Date** 24.06.2025

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**Cite this article:** Yılmaz EÇ. Dynamic thermal cycle ambient simulation under mouth motion; a finite element analysis. *NanoEra*. 2025;5(1):16-21

**Table 1.** Examples of the temperatures of the absorbed fluids and the resulting average minimum and maximum tooth surface temperatures [9]

| Location | Volume drunk (mL) | Hot liquid temp. (°C) | Max. tooth temp. (°C) | Cold liquid temp. (°C) | Min. tooth temp. (°C) |
|---|---|---|---|---|---|
| Incisor labial | - | 60 | 45 | 0 | 15 |
| Incisol palatal | - | < 61 | 58.5 | - | - |
| Molar occlusal | - | < 61 | 53.1 | 0 | 1.0 |
| | - | 63.5 | 53.5 | - | - |
| | - | 58 | 50 | - | - |
| | - | 55 | 47 | - | - |
| Molar palatal | - | 60 | 48.5 | - | - |
| | 30 | 60 | 44.86 | 0 | 21.63 |

**METHOD**

In this study, ANSYS 19 academic version program was preferred for thermal cycle simulation tests of pure titanium material. 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 finite element thermal test analyses. Pure titanium material was designed as square and cylindrical samples on the Space Claim designer software. The ideal ambient properties of pure titanium and test specimens are shown in Figure 1.

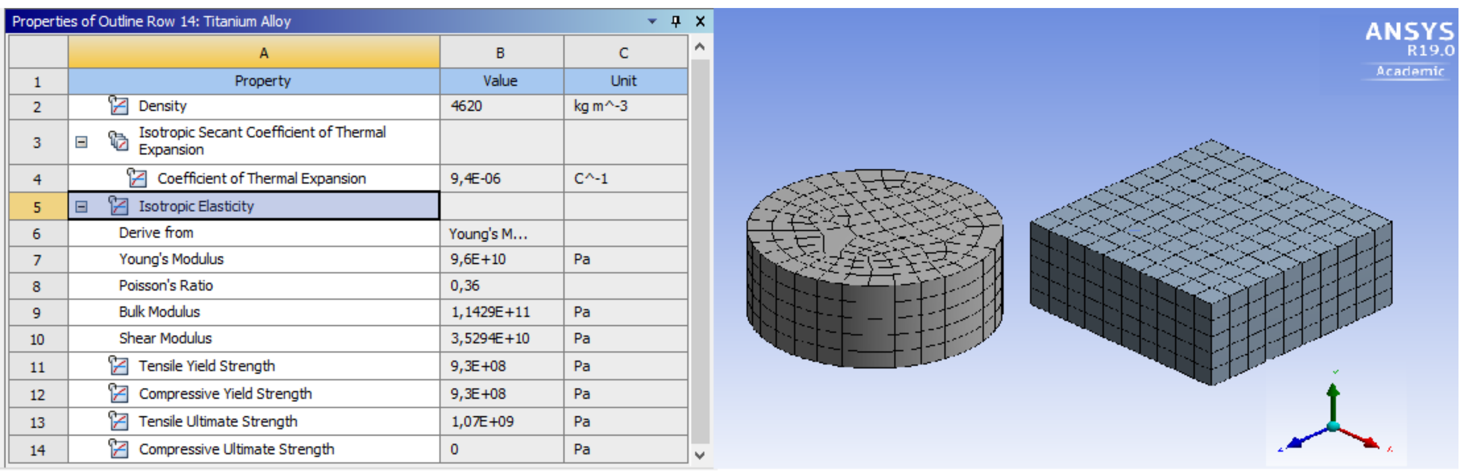


**Figure 1.** The ideal ambient properties of pure titanium and test specimens

The thermal cycle environment experimental studying environment was simulated on a 1/1 scale and designed as 5°C lower limit, 65°C upper limit, 30 seconds waiting period and 2 seconds thermal change period. Figure 2 shows the dynamic thermal cycling test simulation environment. Test specimen with different geometries were placed in the specimen holder shown in Figure 2 and fixed along the geometry expect for thermal surface to simulate the experimental environment. Thus, the geometric change of the test sample due to the temperature difference was controlled through thermal cycle simulation tests. The test mechanism was given to the 65°C fluid medium from the hot water inlet as a first step and waited for 30 seconds. As a second step, the hot water 5°C fluid was thrown into the hot water tank from the fluid outlet and sent to the cold water test environment. This process took about 2 seconds experimentally. The test sample was kept in the cold water environment for 30 seconds and sent to the cold tank from the water outlet in this environment. This process also took about 2 seconds experimentally. Thus, 1 thermal cycle took about 64 seconds experimentally. In the control experimental structure of this process, the programmable logic controller (PLC) was used to control the fluids with solenoid valves. Briefly, the method of activating solenoid valves using a time-delay control structure was used through thermal cycle test simulation. In future studies, this process will be made more sensitive by taking real-time temperature measurements on the test specimen. Thus, the heat absorption rates of different materials will be taken into account in the test structure.

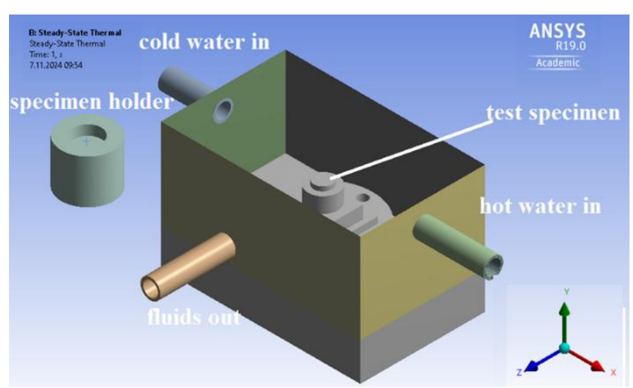


**Figure 2.** Dynamic thermal cycling test simulation environment based real-time PLC Control.

**RESULTS**

In this study, the finite element analysis simulation of the thermal cycle test experiment with real-time control structure was carried out through mouth motion. The 65°C distilled fluid was passed through the test inlet pipe and the test sample was submerged in water. In this case, first the temperature increase occurred in the pipe structure and then the temperature change occurred in the area where the pipe was fixed in the experimental structure. When the fluid reached the test sample, the analysis surface was exposed to the hot fluid and the dead weight of the water was included, creating a mechanical and thermal effect through mouth motion. The mechanical effect in this case created a potential loading depending on the gravitational acceleration and the weight of the water. Although this parameter is ignored in experimental studies, it is an important factor for mechanisms operating in deep water structures. In further studies, this parameter will come to the fore in experimental and finite element analysis simulations of the materials preferred in the ship industry. Figure 3 shows the temperature change behavior of the thermal cycling test device during 1 cycle through mouth motion. First, the 65°C liquid flow from the hot water line reached the chamber in show Figure 3A. The control structure of this situation is realized by the solenoid valve in the time delay time band. When enough fluid enters the chamber, the PLC control unit closes the solenoid valve, ensuring that the hot fluid remains in the chamber for the specified time in Figure 3B. With the completion of the hot cycle period, the second step is to remove the fluid from the chamber by opening the outlet line in the time band and removing the fluid from the sample in Figure 3C. Afterwards, the cold fluid line was filled into the 5 °C fluid test chamber by opening the solenoid valve in Figure 3D. The last step in this process was to discharge the fluid. Thus, 1 thermal cycle was completed. For the second thermal cycle, this process continued until the determined thermal cycle number by showing the same behavior in the same time band.

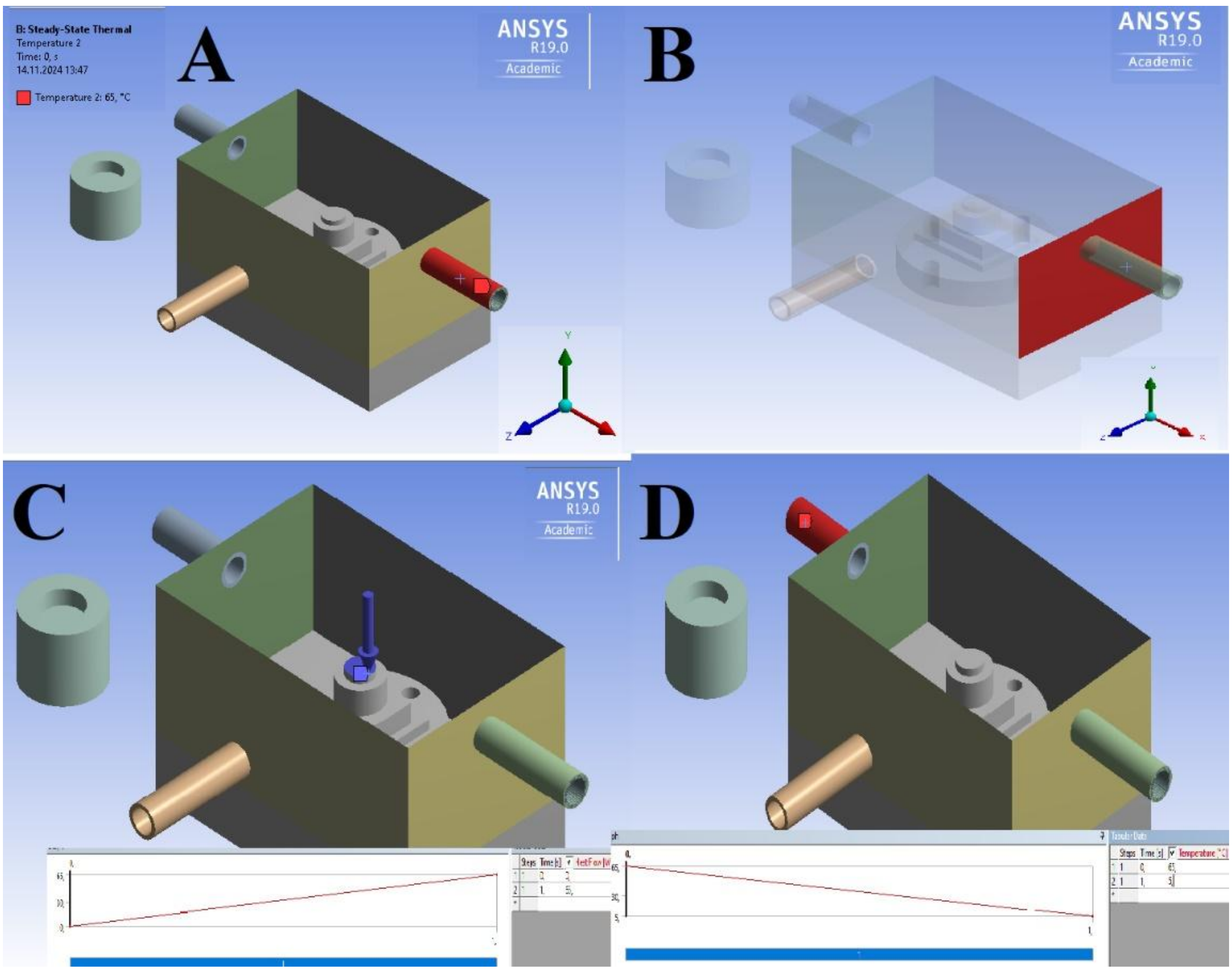


**Figure 3. A-D.** Temperature change behavior of the thermal cycling test device during 1 cycle through mouth motion

Figure 4 shows the thermal temperature environment behavior of pure titanium test specimens with circular and square geometry. The design of the test samples and their behavior under ideal ambient conditions are shown in Figure 4A. The environment where the circular test specimen is at 65°C and the square test specimen is at 5°C is shown in Figure 4B. Figure 4C and Figure 4D show that the square test specimen is included in the heated medium while the circular test specimen is cooling through mouth motion test mechanism.

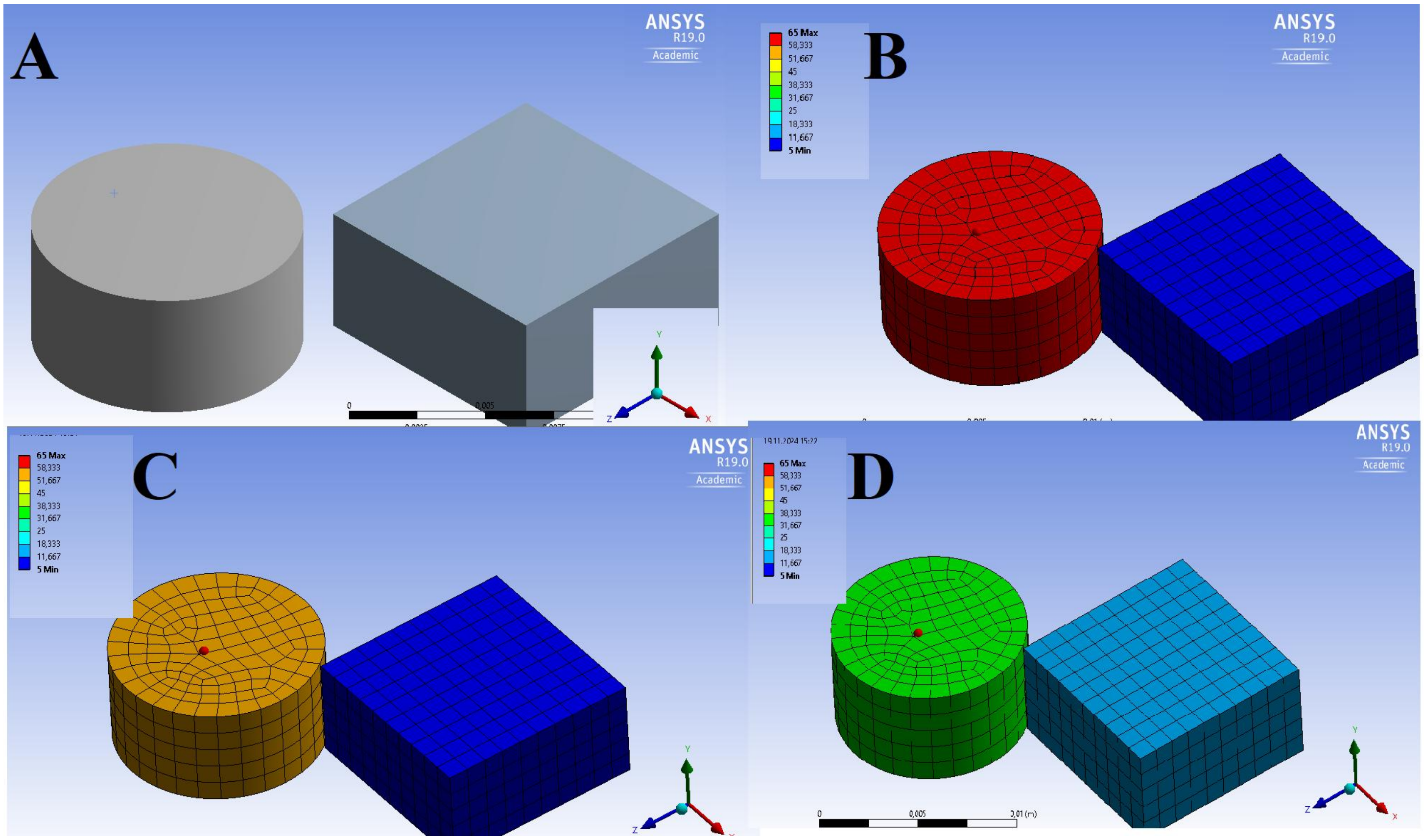


**Figure 4. A-D.** Thermal temperature environment behavior of pure titanium test specimens with circular and square geometry (temperature unit as °C)

## DISCUSSION

The Finite Element Analysis method provides many advantages to researchers in mathematical modeling of experimental studies. The most basic of these advantages can be explained as being able to model in a very short time, being economical, and being more suitable for parameter changes. The ability to model laboratory test experiments one-to-one also provides the opportunity to observe the effects of parameters ignored in laboratory test experiments on the experimental system. Thus, the parameter selection in laboratory test experiments will be more likely to remain in the optimum region. In the literature, many researchers have simulated chewing test experiments *in vitro* and evaluated the mechanical behavior of various biomaterials.[10–13] In experimental studies, it may not always be possible to precisely control standard test parameters. Because the mechanical and control capability of the device that provides the test mechanism is very important for modeling living tissue. For example, the thermal cycling environment was ignored in some chewing test experiments in intra-oral tribology.[14–16] Considering the formation of wear mechanisms during mastication, the occurred of thermal cycling environment is inevitable in both two- and three-component wear mechanism processes. In addition, the type of opposing material selected in the test environment, the chewing force, and the minimum and maximum limits of the thermal cycling environment can positively or negatively affect the mechanical and aesthetic behavior of the test material compared to biomaterials.[17] For these reasons, the evaluation of the parameters that may affect the chewing movement will play an important role in determining the service life of the materials used in the processing process. The parameters of the thermal cycle test procedure (such as exposure time, number of thermal cycles, test temperature range) affect the mechanical and aesthetic behavior of the material. It is reported in the literature that the temperature experienced in the human mouth is approximately 37 degrees. However, this temperature value may vary in variable areas of the mouth structure. Since the material life is evaluated with laboratory test experiments, selecting areas where the temperature is variable will increase the consistency of the test results. Therefore, it is accepted that the temperature is not constant throughout the chewing tests and has a variable structure.[8] The temperature environment in the human oral cavity is dynamic, so it is very difficult to determine the temperature range that is closest to the physiology of the oral cavity. It is important to consider as many variables as possible that can affect tooth temperature. The main sources of temperature stabilization in the mouth are the cheeks, tongue and periodontal tissue surrounding the teeth, which act as a physical barrier that regulates the temperature distribution of the samples.[18] Liquids that people swallow while chewing can be drunk at temperatures between 0 and 100°C, but cooked foods and frozen solids can reach oral temperatures outside this range. The temperature range that an individual can tolerate can vary among different populations and may depend on variables such as the number of teeth, the amount of dentin, the degree of keratinization of the oral mucosa, and the patient's gender in human factory.[19] In addition, dental materials placed in the mouth are subject to continuous and extreme changes in the oral environment due to temperature and pH fluctuations. The temperature cycle in the temperature parameter simulates the entry of hot and cold substances into the oral cavity and shows the linear thermal expansion coefficient relationship between the tooth and the restorative material.[8] The effect of artificial aging of dental materials during thermal cycling can be twofold. This effect causes an improvement in the mechanical behavior of the material, primarily water absorption in composite materials. In the second stage, it can reduce wear by creating a lubricating effect during wear mechanisms. Therefore, it is inevitable for teeth and dental materials to be exposed to thermal stress when the temperature changes. This thermal stress can cause wear mechanisms to lose more material. In addition, this situation can create some problems in terms of material integrity and aesthetics. In a previous experimental study in the literature, it was reported that Durafill composite material experienced more particle loss on the wear surface in thermal cycling test experiments.[20]

## CONCLUSION

The results obtained showed that the temperature distribution in the circular test sample exhibited a more homogeneous distribution behavior than the square test sample. This result reveals the importance of the geometric structure of the test sample in the experimental environment conditions. Therefore, the use of a circular test sample in *in vitro* laboratory thermal cycling experiments will increase the accuracy of the results obtained under mouth motion simulation tests. As a result, the results obtained in this study are expected to mathematically guide the selected parameters in *in vitro* and *in vivo* studies. In addition to the data obtained from this study will increase the test validity of experimental studies by modeling them with finite element analysis simulation.

**Peer-review**: Externally peer-reviewed.

**Conflict of Interest:** The author has no conflicts of interest to declare.

**Financial Disclosure:** The author declared that this study has received no financial support

## REFERENCES

1. Tkachenko S, Datskevich O, Kulak L, Jacobson S, Engqvist H, Persson C. Wear and friction properties of experimental Ti–Si–Zr alloys for biomedical applications. *J Mech Behav Biomed Mater*. 2014;39:61-72. doi:10.1016/j.jmbbm.2014.07.011
2. Cvijović-Alagić I, Cvijović Z, Mitrović S, Panić V, Rakin M. Wear and corrosion behaviour of Ti–13Nb–13Zr and Ti–6Al–4V alloys in simulated physiological solution. *Corros Sci*. 2011;53(2):796-808. doi:10.1016/j.corsci.2010.11.014
3. Yilmaz E, Sadeler R. Effect of different thermal change tests of micro tensile strength behavior bio-composite materials; In vitro study. *Biomed Res J*. 2021;8(1):14. doi:10.4103/bmrj.bmrj_6_21
4. Bordbar-Khiabani A, Gasik M. Electrochemical and biological characterization of Ti–Nb–Zr–Si alloy for orthopedic applications. *Sci Rep*. 2023;13(1):2312. doi:10.1038/s41598-023-29553-5
5. Yilmaz EÇ. Influence of lubricating conditions on the two-body wear behavior and hardness of titanium alloys for biomedical applications. *Comput Methods Biomech Biomed Engin*. 2020;23(16):1377-1386. doi:10.1080/10255842.2020.1804882
6. Yilmaz E, Sadeler R. Effects of contact-stress on wear behavior of zirconia-reinforced lithium silicate glass-ceramic. *Biomed Biotechnol Res J*. 2020;4(1):51. doi:10.4103/bbrj.bbrj_148_19
7. Souza JCM, Bentes AC, Reis K, et al. Abrasive and sliding wear of resin composites for dental restorations. *Tribol Int*. 2016;102:154-160. doi:10.1016/j.triboint.2016.05.035
8. Morresi AL, D'Amario M, Capogreco M, et al. Thermal cycling for restorative materials: Does a standardized protocol exist in laboratory testing? A literature review. *J Mech Behav Biomed Mater*. 2014;29:295-308. doi:10.1016/j.jmbbm.2013.09.013
9. Gale M., Darvell B. Thermal cycling procedures for laboratory testing of dental restorations. *J Dent*. 1999;27(2):89-99. doi:10.1016/S0300-5712(98)00037-2
10. Yılmaz EC, Sadeler R. Investigation of three-body wear of dental materials under different chewing cycles. *Sci Eng Compos Mater*. 2018;25(4):781-787. doi:10.1515/secm-2016-0385
11. Yilmaz EÇ, Sadeler R. Investigation of Two- and Three-Body Wear Resistance on Flowable Bulk-Fill and Resin-Based Composites. *Mech Compos Mater*. 2018;54(3):395-402. doi:10.1007/s11029-018-9750-8
12. Hahnel S, Schultz S, Trempler C, Ach B, Handel G, Rosentritt M. Two-body wear of dental restorative materials☆. *J Mech Behav Biomed Mater*. 2011;4(3):237-244. doi:10.1016/j.jmbbm.2010.06.001
13. Koottathape N, Takahashi H, Iwasaki N, Kanehira M, Finger WJ. Quantitative wear and wear damage analysis of composite resins in vitro. *J Mech Behav Biomed Mater*. 2014;29:508-516. doi:10.1016/j.jmbbm.2013.10.003
14. Lazaridou D, Belli R, Petschelt A, Lohbauer U. Are resin

composites suitable replacements for amalgam? A study of two-body wear. *Clin Oral Investig*. 2015;19(6):1485-1492. doi:10.1007/s00784-014-1373-4
15. Cao L, Zhao X, Gong X, Zhao S. An in vitro investigation of wear resistance and hardness of composite resins. *Int J Clin Exp Med*. 2013;6(6):423-430.
16. Koottathape N, Takahashi H, Iwasaki N, Kanehira M, Finger WJ. Two- and three-body wear of composite resins. *Dent Mater*. 2012;28(12):1261-1270. doi:10.1016/j.dental.2012.09.008
17. Yilmaz E, Sadeler R. Effect of thermal cycling and microhardness on roughness of composite restorative materials. *J Restor Dent*. 2016;4(3):93-96. https://link.gale.com/apps/doc/A461035563/HRCA?u=anon~9db94b3b&sid=googleScholar&xid=0503b871
18. Youngson CC, Barclay CW. A pilot study of intraoral temperature changes. *Clin Oral Investig*. 2000;4(3):183-189. doi:10.1007/s007840000060
19. Barclay CW, Spence D, Laird WRE. Intra-oral temperatures during function. *J Oral Rehabil*. 2005;32(12):886-894. doi:10.1111/j.1365-2842.2005.01509.x
20. Yilmaz EÇ. Effects of thermal change and third-body media particle on wear behaviour of dental restorative composite materials. *Mater Technol*. 2019;34(11):645-651. doi:10.1080/10667857.2019.1611201