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2D and 3D Wear Analysis of 3D Printed and Prefabricated Artificial Teeth

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ABSTRACT

Purpose: This study aimed to assess the 3-body wear of prefabricated and 3D-printed artificial denture teeth.

Materials and methods: Four groups of artificial teeth were used; 3D-printed polymethylmethacrylate (PMMA) teeth (PR) and 3 prefabricated commercially available denture teeth: PMMA (Gnathostar, GN), PMMA (SR Orthotyp PE, SR), and Nanohybrid composite (SR Phonares NHC, PH). The 3-body wear test was performed using a steatite ceramic antagonist in a chewing simulator with 750,000 cycles, temperature 23 ± 2 °C, and force of 50 N. The abrasive medium was composed of ground millet seeds and white rice mixed with distilled water. The teeth were 3D-scanned before and after the wear test. The 3D images were assessed for teeth wear by measuring the volumetric (3D wear) and the vertical (2D wear) substance loss. The one-way analysis of variance followed by Tukey post hoc test was used to statistically obtain the data analysis.

Results: Maximum 3D wear was observed in the PR (51.05 ± 4.53 mm^3), followed by GN (20.22 ± 6.29 mm^3) and SR (12.12 ± 6.29 mm^3) artificial teeth. Minimum wear occurred in the PH teeth (6.24 ± 0.87 mm^3). The analytical differences amongst the groups were statistically significant ($P < .05$) except between PH and SR teeth. For 2D wear measurement, the maximum was seen in the GN teeth (6.29 ± 1.64 mm), followed by PR (5.04 ± 0.83 mm) and then SR (4.53 ± 0.87 mm). The PH teeth (3.09 ± 0.68 mm) again showed minimum wear. Statistically, amongst the groups, the major observable differences ($P < .05$) were between PH and GN, PH and PR, and SR and GN.

Conclusions: Composite resin teeth had a greater wear resistance than acrylic resin teeth and 3D-printed resin teeth, both of which were comparable. Due to the advancement of digital workflows, manufacturers should devote effort to enhancing 3D-printed teeth.

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Introduction

Different materials have been used to fabricate artificial teeth for a removable prosthesis, such as acrylic resin, ceramic, 3D-printed teeth, and resin composite teeth. The most important properties of artificial teeth are their ability to resist wear by the opposing dentition and abrasive food substances. Teeth wear resistance is defined as the ability of the artificial teeth to stay in occlusion as long as possible without changing dimension.[1]

Several studies have investigated the wear of artificial teeth, but results are conflicting.[2–5] This could be because the wear resistance of the artificial teeth is determined by the materials used in teeth production, which affect the microstructure, surface hardness, and strength. Wear resistance seems to vary according to the nature of the opposing material.[6] The suitability of the antagonist for the human enamel must then be considered when replacing missing teeth. Ideally, to reduce teeth wear, artificial teeth must have similar properties to the opposing teeth.[7] One of the factors that increases the risk of teeth wear is the roughness of the external surface of the antagonist.[8] Wear can also occur due to the contact between 2 teeth surfaces during dynamic occlusal movement.[6]

Wear is a complex process, affected by several factors such as the type of abrasive food, parafunctional habit, neuromuscular force, chewing pattern, antagonistic material, and enamel thickness and hardness.[9] The consequences of excessive teeth wear can thus alter occlusion with loss of vertical dimension, decrease in masticatory function, the fatigue

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of masticatory muscles, and temporomandibular joint disorder.[10] Several studies have also observed that teeth wear affects the retention and stability of dentures.[11] By studying artificial teeth wear resistance, one can presumably determine the durability of the removable prosthesis.

Currently, the artificial teeth manufacturing market is flooded with various types, many proposing new and improved features. However, there is a definitive lack of substantial evidence-based information concerning the material components of these products. The acrylic resin teeth that were introduced in the 1930s are considered by many as the right choice due to the low cost in production and easy handling.[1] The chemical bonding of the acrylic resin teeth to the denture base makes it more stable. It can be contoured and shaped easily and has good fracture resistance. However, the wear resistance is low. As a result, new acrylic resin teeth were produced with enhanced properties due to the cross-linking agents, new monomers, and inorganic fillers. Porcelain teeth are considered hard teeth that bond to the denture base mechanically but are prone to breakage or cracks.[12] These are mainly used for their distinction in colour stability and aesthetics.[6] However, they do provide excellent wear resistance, which can increase the natural teeth wear.[13] Composite resin denture teeth, on the other hand, introduced in the 1980s, are a better alternative to the existing artificial teeth in terms of wear resistance.[10,13] Further, 3D-printed teeth that were introduced to the market 2 decades ago are made from methacrylate-based photopolymerised resin, which is then processed and cured by 3D-printing.[14] The mechanical features of 3D-printed teeth, so far, have not been not fully investigated, but they are reported to have good fracture resistance.[13]

The current study aims to evaluate the 3-body wear behaviour of different artificial teeth, namely, 3D-printed resin and 3 commercially available prefabricated denture teeth, with the null hypothesis being that there is no difference in volumetric (3D wear) and vertical (2D wear) substance loss between the different types of artificial teeth tested after the 3-body wear test in a chewing simulator.

Materials and methods

Sample size

The sample size was calculated following the results of the pilot study using statistical software (Minitab 16, Minitab Ltd.), using analysis of variance (ANOVA) with maximum difference of means of 3.37 and a 1.7 estimated pooled standard deviation. Seven cases per group were required to achieve a power of 80% and an alpha error of 0.05. One case was added to each group to anticipate missing data to make a sum of 8 samples per group with a total of 32 teeth.

Specimen preparation

Eight artificial maxillary first premolars were used from each material tested: nanohybrid composite (SR Phonares NHC, PH), 3D-printed resin teeth (PR) (PowerDent), conventional acrylic resin teeth (polymethylmethacrylate [PMMA]) (Gnathostar, GN), and modified acrylic resin teeth (PMMA) (SR Orthotyp PE, SR). Manufacturer, composition, and lot number of the tested materials are listed in Table 1.

To standardise the tested artificial teeth surface, cusps of each tooth specimen were wet-abraded and finished with a 600 to 800 grit abrasive paper to a total depth of 0.5 mm, to obtain a flat area of approximately 2.5 $\times$ 3 mm for loading during the wear test. Teeth were embedded in autopolymerising acrylic resin using custom-made Teflon holders with a diameter of 32 mm. A Ney surveyor was used to ensure that the abraded surface of the buccal cusp was aligned perpendicular to the long axis of the specimen holder. Steatite ceramic balls with a diameter of 6 mm were used as the antagonist material.

Wear testing

Wear test was performed in a dual-axis 8-chamber chewing simulator (chewing simulator CS-8, SD Mechatronik GmbH) (Figure 1), with vertical and horizontal movements between 2 antagonistic specimens in each of the 8 specimen chambers. Vertical load in each masticatory cycle was 5 kg, and horizontal sliding was 2 mm. Temperature was set on (23 $\pm$ 2 °C), similar to room temperature. pH at the beginning of the experiment was measured, and abrasive media was changed everyday to ensure maintaining pH at 7. Each group was loaded with 750,000 chewing cycles, which approximately corresponded to 5 years of clinical service[15] and a force of 50 N. By grinding 30 g of millet seed and 120 g of white rice for 60 seconds, together with 275 mL of distilled water, an abrasive medium was prepared according to Schultz et al.[16]

Table 1 – Tested denture teeth.

	Material	Abbreviation	Manufacturer	Composition (manufacturer's declaration)	Lot number
1	3D resin printed teeth	PR	Promarket Tasarim ve Teknoloji Inc, Istanbul, Turkey	PMMA with auxiliary matters	0621002
2	Gnathostar	GN	Ivoclar-Vivadent, Schaan, Liechtenstein	PMMA	51701
3	SR Orthotyp PE	SR	Ivoclar-Vivadent, Schaan, Liechtenstein	PMMA	YB14FS
4	SR Phonares NHC	PH	Ivoclar-Vivadent, Schaan, Liechtenstein	Nanohybrid (TXM-UDMA, silanised SiO2, urethane dimethacrylate Polymer, PMMA cluster)	015590

PMMA, polymethyl methacrylate; UDMA, urethane dimethacrylate and other methacrylates.

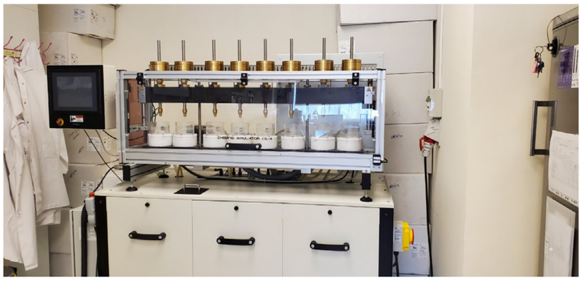

Fig. 1 – Chewing simulator CS-8, SD Mechatronik GmbH.

Wear measurements

All teeth were scanned before and after wear testing using a 3D scanner (InEos Blue, Sirona Dental Systems GmbH) with supporting software, as illustrated in Figure 2. Vertical (2D wear) and volumetric (3D wear) loss were calculated by superimposition of 3D models and subtraction process using 3D software Meshmixer (Autodesk) and MeshLab (Consiglio Nazionale delle Ricerche, National Research Council). For 2D wear, differences were checked on a cross-sectional view of the superimposed models, the cross-section was always running through the buccal cusp tip. Vertical loss of substance was measured by drawing a perpendicular line to the worn tooth surface, from the highest point on the cusp slope in the scanned model before mechanical loading to the deepest point after mechanical loading. The process of obtaining the lost 2D and 3D began by reducing the original before and after meshes. Resultant meshes were repaired by closing the holes. Two reduced meshes were aligned in 2 stages. First alignment was achieved by selecting 4 matching points on before and after meshes (central groove, lingual cusp tip, mesial pit, and distal pit). A global bundle adjustment error-distribution algorithm was implemented to accurately align the 2 meshes (Figure 2B). The alignment step was followed by a Boolean subtraction operation (Figure 2C). The difference mesh was cleaned up, and any hanging surfaces were removed (Figure 2D). Vertical material loss (2D wear) was recorded in mm, and volume loss (3D wear) was recorded in mm^3. For accuracy, all samples were measured 2 times by the same investigator and the concordance correlation coefficient was used to assess intraobserver agreement between the 2 measurements.

Statistical Analysis

Wear data passed the normality test; therefore, a parametric one-way ANOVA was used to analyse the 2D and 3D wear data, followed by Tukey post hoc test with a P value <0.05 considered as statistically significant amongst the different experimental groups. All statistical analyses were performed using GraphPad Prism 5 software version 5.03 (GraphPad Software, Inc.). Data underlying the findings of the study can be obtained from the primary author, Amna S. Al Saadi (email: dr.amna.alsaadi@mohap.gov.ae).

Results

Mean and standard deviation values of the 2D and 3D wear measurements of denture teeth tested are shown in Table 2.

Highest vertical loss was recorded with conventional acrylic teeth GN (6.29 ± 1.64 mm), followed by PR teeth (5.04 ± 0.83 mm), and then SR (4.53 ± 0.87 mm). The least vertical loss was observed in PH teeth (3.09 ± 0.68 mm). Based on Tukey post hoc test, the differences amongst the groups were statistically significant ($P < .05$) in PH and GN, PH and PR, and SR and GN, but not significant between PH and SR, SR and PR, and GN and PR ($P > .05$).

Highest volume loss was observed in the PR group (51.05 ± 4.53 mm^3), followed by conventional acrylic GN teeth (20.22 ± 6.29 mm^3) and then SR teeth (12.12 ± 6.29 mm^3). The least noticeable wear volume loss was in PH teeth (6.24 ± 0.87 mm^3). Based on Tukey post hoc test, differences amongst the

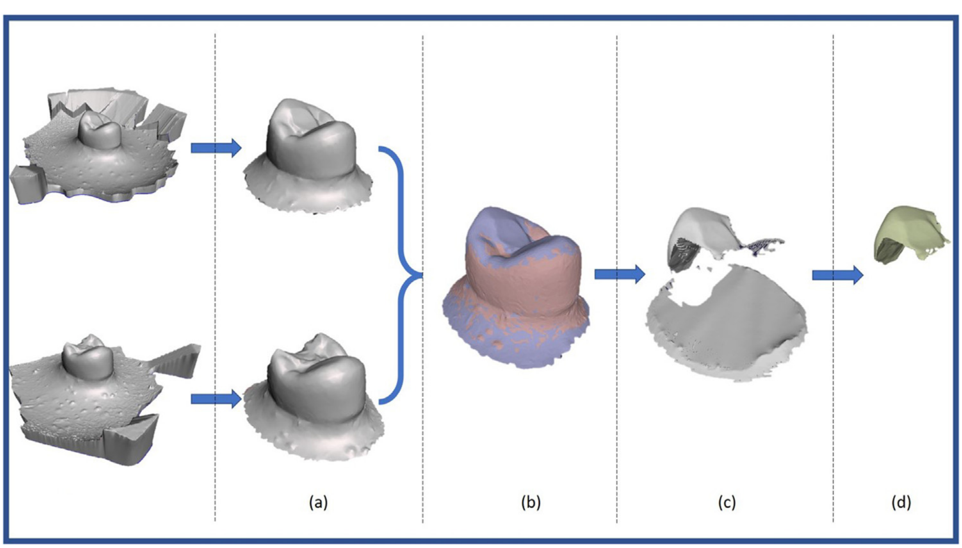

Fig. 2 – A, Tested material before and after the experiment. B, Alignment step. C, Subtraction operation. D, The difference in substance loss.

Table 2 – Mean values (± standard deviation) for vertical and volume tooth loss after wear simulation cycles.

	N	Vertical loss of teeth (mm)	Volume loss of the teeth (mm^3)
3D printed teeth (PR)	8	(5.045 ± 0.83)	$(51.05 \pm 8.02)^c$
Gnathostar (GN)	8	(6.2925 ± 1.64)	(20.2235 ± 6.77)
SR Orthotyp PE (SR)	8	$(4.53375 \pm 0.87)^a$	$(12.12 \pm 2.38)^b$
SR Phonares NHC (PH)	8	$(3.0925 \pm 0.68)^b$	$(6.24 \pm 0.87)^a$

Mean values with different superscript letters are considered statistically different ($P < .05$).
For vertical loss: ^{a}SR and GN, ^{b}PH and GN, PH and PR.
For volume loss: ^{a}PH and GN, PH and PR, ^{b}SR and GN, SR and PR, ^{c}GN and PR.

groups were statistically significant ($P < .05$) in PH and GN, PH and PR, SR and GN, SR and PR, and GN and PR, but not between PH and SR ($P > .05$).

The concordance correlation coefficient used to assess intraobserver agreement between the 2 measurements was between 0.99 and 1, which corresponds to near-perfect agreement.

Discussion

This study aimed to quantifiably measure the amount of wear in different types of artificial teeth. Based on the one-way ANOVA, the material tested significantly affected volume (3D wear) and vertical (2D wear) substance loss ($P < .05$). Thus, the null hypothesis stating that there is no significant difference in the amount of teeth wear between different types of artificial teeth was rejected.

Whilst this study utilised an upper maxillary first premolar specimen, similar to other studies,[9,17,18] comparisons of results should be made with caution because study designs differ. Evaluation of teeth wear can be done either in vitro or in vivo. In vivo testing cannot be standardised to get reliable results due to intra- and intersubject discrepancies in oral temperature, saliva pH, chewing habits, saliva composition, and dietary habits.[11] Artificial saliva was not used in this study because it affects microhardness and amount of wear of the tested material[19]; thus, the in vitro chewing simulator machine was used in current study to provide a more reliable methodology, allowing for superior control of confounding variables.

This study utilised 3-body abrasion, or “rolling abrasion,” where particulate abrasives were used to simulate food bolus between artificial tooth surface under examination and the antagonist surface.[20] An artificial tooth surface that is directly in contact with antagonist materials can lose its substance due to “grooving wear,” which occurs as a result of 2-body abrasion.[21] According to Krejci et al,[22] the terms “grooving wear” and “rolling abrasion” should be used to describe the mechanisms of abrasive wear rather than “2-body abrasion” and “3-body abrasion.” In the current study, both 2D and 3D wear measurements were done.

Wear measurement was done by 3D digital scanning of the samples before and after wear, then the volumetric (3D) and vertical (2D) loss of the worn tooth structure were measured by superimposition and subtraction of the two 3D models. This approach represents a quantitative methodology that has been recommended by several authors due to its accuracy in both clinical and laboratory studies.[9,23,24]

Results indicate that 3D wear measurement is preferred over 2D wear measurements, as it allowed for a more precise analysis of wear loss, which is supported by previous studies.[25–27] Both 2- and 3-body wear phenomena happen in the oral environment, which shows that in vitro studies on 2-body wear resistance only partially relate to the clinical situation. Combining the 2- and 3-body wear assessments considerably increases the significance of in vitro studies on wear resistance.[25] The study by Kadokawa et al investigated the abrasion wear and other abrasive characteristics of a gold alloy, composite resin, porcelain, and human enamel using 2-body and 3-body conditions (PMMA slurry). It was found that the amount of wear values in 3-body wear was significantly less.[28]

For this study, the chewing simulator was employed to replicate vertical movements representing the closing of the mandible and horizontal movements representing lateral excursion movements. The vertical load used in this study was 50 N, which corresponds to the average load of healthy individuals with no abnormal functions, according to a study by Gibbs et al.[29] Taylor et al[30] investigated the longevity of denture use and found it varies between 3 and 10 years, so the number of chewing cycles was set to 750,000, corresponding to approximately 5 years of clinical service.[31]

Standardising shape and size of tooth enamel would have posed a challenge; instead, steatite ceramic spheres of standardised shape and size were used as antagonist material, which are approximately the same size as the human antagonist cusp. Steatite is characterised by similar physical properties to enamel and can substitute for enamel in abrasion tests.[32] Krejci et al[22] found that teeth wear is influenced by the material’s hardness, texture, and surface finish. In this study, by directly measuring the vertical and total volume loss on the teeth specimens, we were able to assess the wear of the teeth in 2 ways.

Nanohybrid composite resin (NHC) demonstrated superior wear resistance in the current study, which is consistent with previous research.[3,4] It contains various fillers that come in many shapes and sizes, along with resin composites and PMMA. Material strength and colour stability are provided by macrofillers, whilst microfillers improve the wear resistance. There is a range of 39.0% to 45.0% of inorganic filler mass in composite resin teeth. A study found that artificial denture teeth containing 40% to 50% inorganic filler have better abrasion resistance than interpenetrating polymer network denture teeth.[33] Alshehri[5] measured the durability and wear of NHC denture teeth compared to interpenetrating polymer network (IPN) and double cross-linked (DCL) PMMA denture teeth and discovered that NHC teeth exhibited significantly more wear than the IPN and the DCL PMMA denture teeth. Heintze et al[34] reported higher wear in NHC than 2 different types of ceramic. However, the study by Stober et al[10] indicates that there was no defining relationship between the chemical composition of 9 different resin-based denture teeth and the level of teeth wear.

Some commercially available acrylic resin teeth that are widely used in dental practice exhibit remarkable wear resistance. SR and GN teeth are frequently chosen because of their good physical properties and affordable price. The tested PMMA resin teeth showed higher volumetric and vertical substance loss than the resin composite teeth. The results showed that the amount of wear in SR is significantly less than with GN. This could be attributed to the composition and multilayer of the SR. The microstructure of conventional acrylic resin teeth differs from that of the modified acrylic resin teeth, as the earlier ones typically contained linear polymer chains. Modified acrylic resin teeth have cross-linking structures containing microfillers or nanofillers, interpenetrating networks, and altered monomer compositions that improve the physical characteristics.[1,10] However, clinical research studies have not detected significant differences in wear patterns between conventional PMMA teeth and improved acrylic teeth (DCL, IPN).[3,35] Another study found that artificial teeth made from urethane dimethacrylate (UDMA) supplemented with inorganic filler particles had higher wear rates than the GN conventional PMMA teeth.[17] Furthermore, Suzuki[36] discovered that the 3-body wear resistance of denture teeth and polymers with a high degree of cross-linking or inorganic fillers wore out more slowly than conventional polymethyl methacrylate.

The 3D printed resin teeth are fabricated from a special material developed specifically for additive manufacturing, which showed similar wear resistance to the conventional acrylic Gnathostar.[36] An experimental study by Chung et al[13] supports the claim that 3D-printed resin material could have better clinical outcomes as milled or self-cured resins. Additionally, 3D-printed resin teeth proved to have similar fracture resistance compared to traditional prefabricated denture teeth.[10] Using an electronic scanning microscope (SEM), an in vitro study evaluated wear resistance by measuring volume loss of 3D-printed resin teeth when opposed by zirconia and metal.

In the case of 3D-printed resin teeth, the wear volume was high when the antagonist was zirconia, and SEM images showed smooth surfaces. The wear was less when the antagonist was metal, but SEM images showed cracked surfaces.[10]

Previous clinical studies on 3D-printed materials concentrated on investigating strength and accuracy. 3D-printed resin material showed comparable elastic modulus to conventional resin material. There was a significant difference in the peak stress between the 3D-printed resin materials and conventional resins.[37] The 3D-printing technology has the potential to provide optimal benefits in dental care. However, further studies are required to examine the compressive, flexural, shear, tensile, and fatigue strength, along with permeability and solubility.

The findings of this study indicate that there is considerable value in investigating the use of resin materials in 3D printing manufacturing for dental restorations, as the conversion of traditional workflow processes to digital workflows has become more prevalent in recent years. Further investigative research involving other newly developed restorative materials and resin teeth are necessary to improve the performance of artificial teeth and update clinical treatment planning in the field of dentistry. Future research needs to concentrate on the physical components of the 3D-printed resin materials and improve the 3D printing technology with additively manufactured multilayered artificial teeth.

Conclusions

Although all the investigated artificial denture teeth showed clinically acceptable wear values, the results also showed a disparity in their behaviours following the 3-body wear test. Resin composite teeth demonstrated superior wear resistance over the conventional acrylic resin teeth and the 3D-printed resin teeth. Because there is a noticeable shift from the traditional dental processes to more progressive dental processes that involve digital workflows, the most appropriate type of artificial teeth should be considered, and enhancement of the 3D-printed materials should be targeted by the manufacturers. Clinical investigation into the manufacturing of resin materials for 3D-printed dental restorations especially has merit. Additionally, 3D wear measurement facilitates more precise analysis of wear loss than 2D measurement.

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Conflict of interest

None disclosed.

REFERENCES

1. Kamonwanon P, Yodmongkol S, Chantarachindawong R, Thaweeboon S, Thaweeboon B, Srikhirin T. Wear resistance of a modified polymethyl methacrylate artificial tooth compared to five commercially available artificial tooth materials. J Prosthet Dent 2015;114(2):286–92.
2. Rahi M, Smaira E, Daou EE. The incidence of prosthetic materials on wear mechanism of antagonist dentition: a review. Int Arab J Dent 2014;5(3):125–30.
3. Ghazal M, Yang B, Ludwig K, Kern M. Two-body wear of resin and ceramic denture teeth in comparison to human enamel. Dent Mater 2008;24(4):502–7.
4. Preis V, Hahnel S, Behr M, Rosentritt M. Contact wear of artificial denture teeth. J Prosthodont Res 2018;62(2):252–7.
5. Alshehri A. The wear of acrylic resin and composite resin teeth against polished and glazed zirconia. Master's Thesis. TheScholarsRepository@LLU: Digital Archive of Research, Scholarship & Creative Works: 2018.
6. Ghazal M, Albashaireh ZS, Kern M. Wear resistance of nanofilled composite resin and feldspathic ceramic artificial teeth. J Prosthet Dent 2008;100(6):441–8.

7. Wang L, Liu Y, Si W, Feng H, Tao Y, Ma Z. Friction and wear behaviors of dental ceramics against natural tooth enamel. J Eur Ceram Soc 2012;32(11):2599–606.
8. Ghazal M, Kern M. The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. J Prosthet Dent 2009;101(5):342–9.
9. Hao Z, Yin H, Wang L, Meng Y. Wear behavior of seven artificial resin teeth assessed with three-dimensional measurements. J Prosthet Dent 2014;112(6):1507–12.
10. Stober T, Lutz T, Gilde H, Rammelsberg P. Wear of resin denture teeth by two-body contact. Dent Mater 2006;22(3):243–9.
11. Jin S, Choi JW, Jeong CM, et al. Evaluating the wear of resin teeth by different opposing restorative materials. Materials (Basel) 2019;12(22).
12. Daou EE. Esthetic prosthetic restorations: reliability and effects on antagonist dentition. Open Dent J 2016;9(1):473–81.
13. Chung YJ, Park JM, Kim TH, Ahn JS, Cha HS, Lee JH. 3D printing of resin material for denture artificial teeth: chipping and indirect tensile fracture resistance. Materials (Basel) 2018;11 (10):1–13.
14. Kessler A, Reymus M, Hickel R, Kunzelmann K-H. Three-body wear of 3D printed temporary materials. Dent Mater 2019;5: 1805–12.
15. Nawafleh N, Hatamleh M, Elshiyab S, Mack F. Lithium disilicate restorations fatigue testing parameters: a systematic review. J Prosthodont 2016;25(2):116–26.
16. Schultz S, Rosentritt M, Behr M, Handel G. Mechanical properties and three-body wear of dental restoratives and their comparative flowable materials. Quintessence Int 2010;41(1):e1–10.
17. Ghazal M, Steiner M, Kern M. Wear resistance of artificial denture teeth. Int J Prosthodont 2008;21(2):166–8.
18. Ghazal M, Hedderich J, Kern M. Wear of feldspathic ceramic, nano-filled composite resin and acrylic resin artificial teeth when opposed to different antagonists. Eur J Oral Sci 2008;116 (6):585–92.
19. Mayworm CD, Camargo SS, Bastian FL. Influence of artificial saliva on abrasive wear and microhardness of dental composites filled with nanoparticles. J Dent 2008;36(9):703–10.
20. Vale Antunes PR. Study of abrasive resistance of composites for dental restoration by ball-cratering. Wear 2003;255:990–8.
21. Uehara PN, Iegami CM, Tamaki R, Ballester RY, de Souza RM, Laganá DC. Analysis of behavior of the wear coefficient in different layers of acrylic resin teeth. J Prosthet Dent 2019;121 (6):967. e1-967.e6.
22. Krejci I, Lutz F, Reimer M, Heinzmann JL. Wear of ceramic inlays, their enamel antagonists, and luting cements. J Prosthet Dent 1993(April):167–89.
23. Perry R, Kugel G, Kunzelmann KH, Flessa HP, Estafan D. Composite restoration wear analysis: conventional methods vs. three-dimensional laser digitizer. J Am Dent Assoc 2000;131 (10):1472–7.
24. DeLong R. Intra-oral restorative materials wear: rethinking the current approaches: how to measure wear. Dent Mater 2006;22(8):702–11.
25. Hahnel S, Behr M, Handel G, Rosentritt M. Two-body wear of artificial acrylic and composite resin teeth in relation to antagonist material. J Prosthet Dent 2009;101(4):269–78.
26. Mello PC, Coppedê AR, Macedo AP, de Mattos M da GC, Rodrigues RCS, Ribeiro RF. Abrasion wear resistance of different artificial teeth opposed to metal and composite antagonists. J Appl Oral Sci 2009;17(5):451–6.
27. Benetti AR, Larsen L, Dowling AH, Fleming GJP. Assessment of wear facets produced by the ACTA wear machine. J Dent 2016;45(2016):19–25.
28. Kadokawa A, Suzuki S, Tanaka T. Wear evaluation of porcelain opposing gold, composite resin, and enamel. J Prosthet Dent 2006;96(4):258–65.
29. Gibbs CH, Mahan PE, Lundeen HC, Brehnan K, Walsh EK, Holbrook WB. Occlusal forces during chewing and swallowing as measured by sound transmission. J Prosthet Dent 1981;46 (4):443–9.
30. Taylor M, Masood M, Mnatzaganian G. Longevity of complete dentures: a systematic review and meta-analysis. J Prosthet Dent 2021;125(4):611–9.
31. DeLong R, Douglas WH. An artificial oral environment for testing dental materials. IEEE Trans Biomed Eng 1991;38 (4):339–45.
32. Yilmaz EC, Sadeler R. Investigation of three-body wear of dental materials under different chewing cycles. Sci Eng Compos Mater 2018;25(4):781–7.
33. von Fraunhofer JA, Razavi R, Khan Z. Wear characteristics of high-strength denture teeth. J Prosthet Dent 1988;59(2):173–5.
34. Heintze SD, Zellweger G, Grunert I, Muñoz-Viveros CA, Hagenbuch K. Laboratory methods for evaluating the wear of denture teeth and their correlation with clinical results. Dent Mater 2012;28(3):261–72.
35. Park JM, Ahn JS, Cha HS, Lee JH. Wear resistance of 3D printing resin material opposing zirconia and metal antagonists. Materials (Basel) 2018;11(6):1–11.
36. Suzuki S. In vitro wear of nano-composite denture teeth. J Prosthodont 2004;13(4):238–43.
37. Tahayeri A, Morgan MC, Fugolin AP, et al. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater 2018;34(2):192–200.