Two-body wear and surface hardness of occlusal splint materials

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The aim of this in vitro study was to evaluate the wear and surface hardness of nine materials for conventional manufacturing, subtractive milling, and 3D printing of occlusal splints, as well as to evaluate the differences in wear and surface hardness between rigid and flexible 3D-printed occlusal splint materials. Two-body wear and Vickers hardness tests were performed. The vertical wear depth and Vickers hardness values were statistically analyzed. Vertical wear depth and surface hardness values were statistically significant among the investigated materials (p<0.05). The lowest vertical wear depth was observed for the heat-cured resin (27.5±2.4 µm), PMMA-based milled material (30.5±2.8 µm), and autopolymerizing resin (36.7±6.3 µm), with no statistical difference (p≥0.05). Flexible 3D-printed and CAD-CAM milled polycarbonate-based splint materials displayed lower surface hardness and higher wear than the PMMA-based materials. PMMA-based splint materials displayed the most consistent surface hardness and wear resistance regardless of the manufacturing technology.

Keywords: Two-body wear, Occlusal splints, 3D printing, CAD/CAM, Surface hardness

INTRODUCTION

Temporomandibular joint and muscle disorders (TMJDS) are the second most frequent musculoskeletal diseases causing pain and impairment¹. Disorders are associated with recurring or chronic pain and dysfunction of the jaw joint, as well as its related muscles and supporting structures. TMJDS affect between 5% and 12% of the population with a higher prevalence rate among young people and women². Intraoral occlusal splints are one of the most prevalent treatments for symptomatic TMJDS, and are shown to be effective in 70–90% of cases²,³. The mechanism of action of occlusal splints can be explained by disrupting the cycle of neuromuscular reflex contraction and inducing muscle relaxation in patients with parafunctional habits. Additionally, they protect teeth from wear and mobility caused by clenching and grinding, distribute the occlusal force exerted on the teeth, and relocate the jaws and condyles into centric relation².

Occlusal splints are often made of polymers. They can be conventionally fabricated by using traditionally heat-cured polymethyl methacrylate (PMMA), vacuum-formed thermoplastic resins, or autopolymerizing PMMA⁴–⁷. Alternatively, computer-aided design and computer-aided manufacturing (CAD-CAM) technologies can be used for the digital production of occlusal splints⁸. A variety of prefabricated standard blanks made of high-performance polymers are available on the market for milling precisely fitted splints, with superior or at least equivalent properties compared to conventional ones⁷,⁸. Furthermore, occlusal splints have been additively manufactured by three dimensional (3D) printing⁹–¹¹, which was presented for the first time in 2013¹². Including ultra violet (UV) absorbers into the resin has made it possible to print transparent objects, which is especially useful for the production of occlusal devices, implant drilling guides, and clear surgical models⁷,¹³. Such technologies enable the rapid and simplified implementation of various treatment options while enhancing the quality control process and employing a wider range of materials¹⁴.

Hard and soft splints have been prescribed as a conservative treatment for TMJDS¹⁵,¹⁶. Soft splints, with their flexible and resilient material properties are able to readily disperse the heavy stresses experienced during parafunctional activities with a high level of patient tolerance¹⁶. Hard splints aim at reducing TMJDS symptoms by modifying the occlusal equilibrium, correcting the vertical dimension, and rectifying condylar position¹⁷. Previous studies¹⁵,¹⁶ reported that either a hard or soft orthopedic device can be successfully utilized to alleviate muscular pain in individuals with TMJDS. However, minimal occlusal changes have been associated with the use of soft occlusal splints¹⁸,¹⁹.

Splints are considered as orthotic devices since they are used to protect the dentation from parafunctional habits, such as diurnal or nocturnal bruxism²,²⁰–²². Maximum occlusal forces in patients with bruxism range from 450 to 650 N²⁸, with a mean of 380 N²⁸. Therefore, wear resistance and surface hardness of these materials is of clinical importance. Materials with inadequate wear resistance may develop wear facets, which hinder occlusal contact stability and reduce the appliance lifespan²⁰,²⁸.

The aim of this in vitro study was to evaluate the
wear and surface hardness of nine commercially available materials for conventional manufacturing, subtractive milling and 3D printing of occlusal splints, as well as to evaluate the differences in surface hardness and wear between rigid and flexible 3D-printed occlusal splint materials. The first research null hypothesis was that the different splint materials would have similar wear and surface hardness, while the second hypothesis was that there would be no differences in surface hardness and wear between rigid and flexible 3D-printed occlusal splint materials.

### MATERIALS AND METHODS

#### Preparation of specimens

A total of nine different occlusal splint materials were evaluated, which were either heat-cured, autopolymerized, milled, or 3D-printed (Table 1). One of the tested 3D-printed materials is intended for the fabrication of rigid splints, while the rest are used for flexible splints.

| Material          | Manufacturer                        | Resin type based on manufacturing technique | Chemical composition from the manufacturer                                                                 |
|-------------------|-------------------------------------|--------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Paladon 65        | Kulzer, Hanau, Germany               | Heat-cured resin                           | Liquid: methylmethacrylate (>90%); tetramethylene dimethacrylate (≥1–≤5%); p-Mentha-1,4-diene (<0.25%)  |
|                   |                                     |                                            | Powder: (based on methacrylate copolymersomers) methylmethacrylate (≥1–≤5%); dibenzoyl peroxide (≥0.25–<1%) |
| Palapress         | Kulzer                              | Autopolymerizing resin                     | Liquid: methylmethacrylate (>90%); tetramethylene dimethacrylate (≥1–≤5%); maleic acid (<0.1%); 2-Hydroxy-4-methoxy benzophenone (≤0.25%); mequinol (<1%); Quaternary ammonium compounds, tri-C8-10-alkylmethyl, chlorides (≥0.025–<0.25%) |
|                   |                                     |                                            | Powder: (based on methacrylate copolymer) dibenzoyl peroxide (≥1–<2.5%); methyl methacrylate (≥1–≤5%); 1-Benzyl-5-phenylbarbitursäure (≥0–≤5%) |
| Cast              | Degos Dental, Regenstauf, Germany   | CAD-CAM milled resin discs                 | PMMA                                                                                                    |
| Aqua              | Degos Dental                        | CAD-CAM milled resin discs                 | PMMA                                                                                                    |
| Temp Premium      | Zirkonzahn, South Tyrol, Italy       | CAD-CAM milled resin discs                 | Polycarbonate                                                                                           |
| Flexible Transpa  |                                     |                                            |                                                                                                          |
| IMPRIMO LC Splint | Scheu-Dental, Iserlohn, Germany     | Light curing resin for 3D printing of splints with relative flexibility (rigid splints)                | (Methacrylate-based resin) esterification products of 4,4’-isopropylidenediphenol, ethoxylated and 2-methylprop-2-enoic acid (>95%); Diphenyl-(2,4,6-trimethylbenzoyl)phosphine oxide (<2%) |
| IMPRIMO LC Splint flex | Scheu-Dental           | Light curing resin with high flexibility and thermo-active memory effect for 3D printing of transparent occlusal splints as well as for bruxism and lower jaw protrusion splints | (Methacrylate-based resin) methacrylate monomer 1(<60%); methacrylate monomer 2 (<40%); methacrylate monomer 3 (<2%), photo initiator (2%) |
| KeySplint Soft    | Keystone, Singen, Germany           | Light curing resin for 3D printing of flexible dental splints and night guards                       | Proprietary Ingredient                                                                                   |
| V-Print splint comfort | VOCO, Cuxhaven, Germany          | Light-curing resin for the generative production of thermoflexible dental, therapeutic splints     | Aliphatic acrylate (25–50%); triethylene glycol dimethacrylate 5-(10%); Diphenyl-(2,4,6-trimethylbenzoyl)phosphine oxide (<2.5%) |
the fabrication of occlusal splints with high flexibility.

To obtain heat-cured and autopolymerizing resin specimens, the respective components were mixed according to the manufacturer’s instructions and placed in Teflon molds, that were then transferred to a pressure pot (Ivomat IP3, Ivoclar Vivadent, Schaan, Liechtenstein) for curing. Autopolymerizing resin specimens were cured for 15 min in water bath at a temperature of 55°C and a pressure of 200 kPa, while heat-cured specimens were cured in a water bath at 90°C for 30 min and then allowed to cool slowly in the water bath. For the CAD-CAM milled groups, a puck of the material was cut to the proposed dimensions at low speed using a water-cooled diamond saw (Secotom 50, Struers, Ballerup, Denmark). For 3D-printed splint materials, an STL file with specimen dimensions was created in AutoCAD (Autodesk, San Rafael, CA, USA) and printed in a 3D printer (Asiga MAX™, Asiga, Sydney, Australia) at 90° orientation to the build platform and with a layer thickness of 100 μm, followed by postcuring (Form cure, Formlabs, Berlin, Germany) according to the manufacturer’s instructions. Wet polishing of the specimens was performed with a polishing machine (LabPol-21, Struers) using 800 and 1200 grit FEPA silicon carbide abrasive papers (Buehler, NY, USA).

Wear test
Similar to prior studies26,27, four specimens of each splint material (thickness: 2 mm, length: 10 mm, width: 15 mm) were tested for wear. Each specimen was mounted to an acrylic resin block and polished sequentially on a rotary machine using silicon carbide sheets with grain sizes up to 4000 grit FEPA. Specimens were stored in water at 37°C for 24 h before testing. A chewing simulator machine (CS-4.2, SD Mechatronik, Feldkirchen-Westerham, Germany) was utilized for conducting the two-body wear test, which comprises two chambers simulating vertical and horizontal movements in the presence of water at the same time. Each chamber has a lower plastic sample holder for inserting the specimen, as well as an upper antagonist for retaining the loading tip. The manufacturer’s standard loading tips (Steatite ball, 6 mm) were embedded in autopolymerizing acrylic resin material within a plastic ring, and then fixed in the upper antagonist with a fastening screw. A chewing simulation was performed at 1.5 Hz with vertical weight of 2 kg, yielding 20 N of chewing force. Each specimen was exposed to 15,000 loading cycles. Wear patterns were scanned with a 3D optical microscope (Bruker Nano, Berlin, Germany), and then analyzed with Vision64 Map software for material loss measurements. Total wear depth values (μm) were obtained from various sites, according to the average of the deepest points of all profile scans.

Additionally, after evaluating the vertical wear depth, representative specimens of each material were examined by scanning electron microscopy (SEM; JSM 5500, JEOL, Tokyo, Japan) to analyze the wear facets and surface features. Before SEM examination, the specimens were gold sputtered with a gold layer in a vacuum evaporator using a sputter coater (BAL-TEC SCD 050 Sputter Coater, BAL-TEC, Balzers, Liechtenstein).

Surface hardness measurement
The Vickers surface hardness (VHN) of dry and water-stored (30 days at 37°C) bar specimens (4×10×10 mm²) was measured using a microhardness testing device (Duramin-5, Struers) with a load of 1.96 N applied for 15 s. The specimens were cleaned in an ultrasonic cleaning device (Quantrex 90, L&R Ultrasonics, Kearny, NJ, USA) in deionized water for 10 min before testing. An average of three measurements was calculated from each specimen (n=16/material). The imprints’ diagonal lengths were measured with the aid of the eyepiece operator of the testing machines and then used in the calculation of VHN values.

Statistical analysis
Statistical software was used to conduct the analysis (SPSS V25, IBM, Armonk, NY, USA). Vertical wear depth and surface hardness data were analyzed by using one-way ANOVA while applying Dunnett’s T3 from multiple comparison tests to determine the differences between materials. To compare the values of surface hardness of dry and water-stored specimens for each group of materials separately, the independent samples t test was used. The results of the analysis were presented as means and standard deviations, and a p value of 0.05 was considered significant. A Pearson correlation coefficient was made to evaluate the relationship between the vertical wear depth and dry surface hardness values of the investigated splint materials.

RESULTS

Figure 1 and Table 2 demonstrate descriptive statistics for the obtained values of vertical wear depth and surface hardness. There was a statistically significant difference among the investigated materials in the vertical wear depth (p<0.001) and surface hardness of dry (p<0.001) and water-stored (p<0.001) specimens.

The lowest vertical wear depth was observed in Paladon 65 (27.5±2.4 μm), Cast (30.5±2.8 μm), and Palapress (36.7±6.3 μm), with no statistical difference (p>0.05). Meanwhile, Temp Premium Flexible Transpa, V-Print splint comfort, and IMPRIMO LC Splint flex had the highest vertical wear depth values, with a statistically non-significant difference from each other (p=1.000, p=0.708, p=0.999). Interestingly, the flexible 3D-printed splint material, KeySplint Soft was not statistically different from Palapress (p=0.991), Cast (p=0.099), and Aqua (p=1.000), while being significantly lower than the rigid 3D-printed splint material, IMPRIMO LC Splint (p=0.037). The other two flexible 3D-printed splint materials, V-Print splint comfort and IMPRIMO LC Splint flex were significantly higher than IMPRIMO LC Splint (p<0.05).

Figure 2 described SEM images of the tested materials after chewing simulation. Materials
Fig. 1 Mean vertical wear depth values (μm) of tested splint materials. Different letters inside bar indicate a statistically significant difference (p<0.05) between materials. Error bars represent standard deviation (SD).

Table 2 Mean Vickers hardness (VHN) values of tested materials

| Material                  | Vickers hardness (VHN) Mean±SD | p value (Independent samples t test) |
|---------------------------|---------------------------------|-------------------------------------|
|                           | Dry                             | Water                              |
| Paladon 65                | 18.5±0.5a                       | 16.4±0.2a*                         | <0.001 |
| Palapress                 | 18.3±1.2a                       | 15.6±0.2e*                         | <0.001 |
| Cast                      | 20.4±0.6e                       | 16.8±0.3e*                         | <0.001 |
| Aqua                      | 19.1±0.6e                       | 17.9±0.4e*                         | <0.001 |
| Temp Premium Flexible Transpa | 14.3±0.3e                      | 13.7±0.2e*                         | <0.001 |
| IMPRIMO LC Splint         | 17.9±0.8e                       | 12.0±0.9e*                         | <0.001 |
| KeySplint Soft            | 5.3±0.2e                       | 5.3±0.2e*                          | 0.737  |
| IMPRIMO LC Splint flex    | 5.1±0.7e                       | 3.7±1.1e*                          | 0.010  |
| V-Print splint comfort    | 5.5±0.9e                       | 3.5±0.6e*                          | <0.001 |
| p value (one-way ANOVA)   | <0.001                          | <0.001                             |

Different superscript letters indicate significant differences (p<0.05)
*indicates a statistical difference between dry and water-stored specimens of the same material.

specimens displayed visual signs of wear in the form of pits, valleys, scratches, cracks and irregularities. There were differences in wear trends and facet size among the investigated materials. All materials showed grooves oriented parallel with the sliding directions. Paladon 65, Palapress, Aqua, Cast, and IMPRIMO LC Splint materials showed uniform wear facets. Plastic deformation was noticed in the wear facets of IMPRIMO LC Splint flex, V-Print splint comfort, and KeySplint Soft. Paladon 65 and Cast showed a smoother surface at high magnification.

As seen in Table 2, water storage tended to cause a significant reduction in surface hardness for all of the materials except KeySplint Soft (p=0.737). The milled PMMA-based resins, Aqua and Cast, respectively displayed the highest surface hardness after water storage. In addition, Paladon 65 was not significantly different from Cast (p=0.163). While the lowest surface
hardness was displayed by the three flexible additively manufactured splint materials, KeySplint Soft, IMPRIMO LC Splint flex, and V-Print splint comfort \((p>0.05)\). A relatively moderate correlation was detected between the vertical wear depth and the surface hardness \(r^2=-0.596, \ p<0.001\) for the investigated materials.

**DISCUSSION**

In this *in vitro* study, the surface hardness and material surface wear of various conventionally manufactured, milled, or 3D-printed occlusal splint materials with variable degrees of flexibility were investigated. While clinical studies have significant limitations, such as complex procedures, high cost, time constraints, and metrological and analytical difficulties\(^{29}\), laboratory studies are commonly used to evaluate the wear resistance of a material. Such studies are useful for understanding the basic wear mechanisms\(^{30}\). Statistical analysis revealed significant differences in the evaluated aspects between materials. At the same time, significant differences were found between rigid and flexible 3D-printed splint materials. Consequently, the null hypotheses of the study were rejected.

Wear can be defined as the amount of material removed. Unlike restorative materials, occlusal devices are not exposed to abrasive intermediate substrates such as food. Therefore, a 2-body wear test was performed using a chewing simulator that complies with wear test guidelines\(^{30,31}\). The test load was set at 20 N\(^{26,27,31,32}\), however, load values of 50 N\(^{7,33}\) and 5 N\(^{25}\) have been documented in the literature. Considering the anisotropicity of additively manufactured splints\(^{34,35}\), all the tested specimens were printed with a layer thickness of 100 μm while the printing angle was 90°.

The current study showed that the differences in the investigated properties between materials were not only related to the different manufacturing technologies, but also to their chemical composition. PMMA-based (conventionally manufactured and CAD-CAM milled) occlusal splint materials had the lowest surface wear. While both CAD-CAM milled polycarbonate and additively manufactured flexible splint materials, excluding KeySplint Soft, displayed the highest wear. Furthermore, significant differences in wear behavior and surface hardness were observed between rigid and flexible 3D-printed splint materials. The latter displayed plastic deformation after wear testing, as shown by SEM examination (Figs. 2G, H, I). The flexible resins used in 3D printing are UV-curable elastomers characterized by a low modulus of elasticity and low Shore hardness, but with higher flexibility, elongation at break, and elastic rebound\(^{36}\). The mechanical behavior of photocurable resins used for additive manufacturing can be controlled by modifying their composition which is based on liquid monomers, oligomers, and photoinitiators\(^{7,37,38}\). Patel *et al.*\(^{36}\) were able to increase the stretchability of a printable elastomer up to 1,100% by mixing a monofunctional monomer of epoxy aliphatic acrylate (EAA) with aliphatic urethane diacrylate (AUD) oligomer at different ratios.
Unfortunately, the reported compositions for the 3D printing resin products are quite general, vague, and provide extremely limited information, as seen in Table 1, making it difficult to explain the results based on compositions.

Due to the variation in wear test parameters such as wetting medium, indenter material and design, number of chewing cycles, applied movements/rotations, and assessment techniques, an absolute comparison of results between published studies was not applicable. Grymak et al. found that 3D-printed splint materials exhibited lower wear resistance than the heat-cured and CAD-CAM milled PMMA materials. In contrast, in the study by Wesemann et al., conventional, milled, and additively manufactured occlusal splints displayed similar wear resistance after 200,000 loading cycles at 20 N and 50 N, respectively.

Hardness is particularly significant since it shows the ability of a material to resist scratches and applied occlusal loads. Although some studies showed a correlation between surface hardness and wear resistance, others differed. Since occlusal devices are susceptible to intraoral moisture, surface hardness was measured both in dry specimens and after 30 days of water storage at 37°C. Water storage led to a significant decrease in surface hardness for the majority of the investigated materials, especially the additively manufactured ones, which recorded a decrease between 27.5% and 36.4%. This could be explained by the previously reported higher water absorption for sterlithographically processed photopolymers due to microscopic voids between resin layers, which adversely affect their mechanical properties. While CAD-CAM milled and conventional PMMA-based splint materials were the hardest, the 3D-printed materials, especially the flexible ones, displayed the lowest surface hardness values. In a study conducted by Prpic et al., milled and conventional acrylic-based resin materials were harder than 3D-printed materials. The manufacturing processes of CAD-CAM milled blocks result in dense packing of the PMMA material creating a homogeneous porosity-free structure. On the other hand, in 3D printing, layers are deposited parallel to the loading direction, resulting in low mechanical properties, while the adhesion between successive layers is lower than the strength within the structure. Moreover, acrylic ester-based monomers used in 3D printing have comparatively low double bond conversion compared to standard acrylic resins.

Although thermoplastic resins such as polycarbonates are known for their high impact strength, fracture resistance, and flexibility, they exhibited lower wear resistance and surface hardness than PMMA-based polymers, which was consistent with previous studies.

Despite flexible splints may be superior in terms of patient tolerance, rigid PMMA-based ones would be more convenient for bruxism patients and long-term treatment due to their higher wear resistance and surface hardness. The results of the study suggest differences between materials fabricated by different techniques, which should be taken in consideration when selecting a material for the fabrication of occlusal splints depending on the patient situation and needs.

A limitation of the present study was the lack of wear testing after prolonged water storage. In addition, the influence of the printing direction as well as the layer thickness of the 3D-printed splint materials was not investigated.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The wear and surface hardness of occlusal splints depend more on the material composition rather than the manufacturing technology.
2. PMMA-based materials had the most consistent surface hardness and wear resistance regardless of the manufacturing technology.
3. Flexible 3D-printed and CAD-CAM milled polycarbonate-based resins displayed lower surface hardness than the PMMA-based splint materials.
4. With the exception of KeySplint Soft, the flexible 3D-printed and milled polycarbonate-based splint materials exhibited the greatest wear among the investigated materials, potentially limiting their use for bruxism patients and long-term treatments.

REFERENCES

1) Prevalence of TMJD and its Signs and Symptoms [Internet], [cited 2022 Apr 5]. Available from: https://www.nidcr.nih.gov/research/data-statistics/facial-pain/prevalence
2) Riley P, Glenny AM, Worthington HV, Jacobsen E, Robertson C, Durham J, et al. Oral splints for temporomandibular disorder or bruxism: A systematic review. Br Dent J 2020; 228: 191-197.
3) Benli M, Eker Gümüş B, Kahraman Y, Gökçen-Rohlig B, Evlioglu G, Huck O, et al. Surface roughness and wear behavior of occlusal splint materials made of contemporary and high-performance polymers. Odontology 2020; 108: 240-250.
4) Gil-Martínez A, Paris-Alemay A, López-de-Uralde-Villanueva I, La Touche R. Management of pain in patients with temporomandibular disorder (TMD): challenges and solutions. J Pain Res 2018; 11: 571-587.
5) Berntsen C, Kleven M, Heian M, Hjortsjö C. Clinical comparison of conventional and additive manufactured stabilization splints. Acta Biomater Odontol Scand 2018; 228: 191-197.
6) Cass CA, Tregaskes-JN. Occlusal splint fabrication. J Prostheth Dent 1978; 40: 461-463.
7) Lutz AM, Hampe R, Roos M, Lünkmann N, Eichberger M, Stawarczyk B. Fracture resistance and 2-body wear of 3-dimensional–printed occlusal devices. J Prostheth Dent 2019; 121: 166-172.
8) Gibreel M, Perea-Lowery L, Vallittu PK, Lassila L. Characterization of occlusal splint materials: CAD-CAM versus conventional resins. J Mech Behav Biomed Mater 2021; 124: 104813.
9) Marcel R, Reinhard H, Andreas K. Accuracy of CAD/CAM-fabricated bite splints: milling vs 3D printing. Clin Oral
10) Perea-Lowery L, Gibreel M, Vallittu PK, Lassila L. Evaluation of the mechanical properties and degree of conversion of 3D printed splint material. J Mech Behav Biomed Mater 2021; 115: 104254.

11) Reymus M, Lümkemann N, Stawarczyk B. 3D-printed material for temporary restorations: Impact of print layer thickness and post-curing method on degree of conversion. Int J Comput Dent 2019; 22: 231-237.

12) Salmi M, Palohéimo KS, Tuomi J, Ingman T, Mäkitie A. A digital process for additive manufacturing of occlusal splints: A clinical pilot study. J R Soc Interface 2013; 10: 20130203.

13) Stansbury JW, Idacavage MJ. 3D printing with polymers: Challenges among expanding options and opportunities. Dent Mater 2016; 32: 54-64.

14) Anderson J, Weallens J, Ray J. Endodontic applications of 3D printing. Int Endod J 2018; 51: 1005-1018.

15) Pettengill CA, Growney MR, Schoff R, Kenworthy CR. A pilot study comparing the efficacy of hard and soft stabilizing appliances in treating patients with temporomandibular disorders. J Prosthodont 1998; 79: 168-168.

16) Seifeldin SA, Elhayes KA. Soft versus hard occlusal splint therapy in the management of temporomandibular disorders (TMDs). Saudi Dent J 2015; 27: 208-214.

17) Dylina TJ. A common-sense approach to splint therapy. J Prosthod Dent 2001; 86: 539-545.

18) Singh BP, Berry DC. Occlusal changes following use of soft occlusal splints. J Prosthod Dent 1985; 54: 711-715.

19) Wright E, Anderson G, Schulte J. A randomized clinical trial of intraoral soft splints and palliative treatment for masticatory muscle pain. J Orofac Pain 1995; 9: 192-199.

20) Casey J, Dunn WJ, Wright E. In vitro wear of various orthotic device materials. J Prosthodont 2003; 90: 498-502.

21) Green JI. Prevention and management of tooth wear: The role of dental technology. Prim Dent J 2016; 5: 30-34.

22) Manfredini D, Winocur E, Guarda-Nardini L, Paesani D, Lobbezoo F. Epidemiology of bruxism in adults: A systematic review of the literature. J Orofac Pain 2013; 27: 99-110.

23) Rosar JV, Barbosa T de S, Dias IJOV, Kobayshi FY, Costa YM, Gavião MBD, et al. Effect of interocclusal appliance on bite force, sleep quality, salivary cortisol levels and signs and symptoms of temporomandibular dysfunction in adults with sleep bruxism. Arch Oral Biol 2017; 82: 62-70.

24) Domagala I, Przystupa K, Firlej M, Pieniak D, Gil L, Borucka A, et al. Analysis of the statistical comparability of the hardness and wear of polymeric materials for orthodontic applications. Materials 2021; 14: 2925.

25) Huettel F, Kustermann A, Kuscu E, Gois-Gerstorfer J, Spintzky S. Polishability and wear resistance of splint material for oral appliances produced with conventional, subtractive, and additive manufacturing. J Mech Behav Biomed Mater 2017; 75: 175-179.

26) Oja J, Lassila L, Vallittu PK, Garoushi S. Effect of accelerated aging on some mechanical properties and wear of different commercial dental resin composites. Materials 2021; 14: 2769.

27) Garoushi S, Lassila L, Vallittu PK. Impact of fast high-intensity versus conventional light-curing protocol on selected properties of dental composites. Materials 2021; 14: 1381.

28) Yip KHK, Smales RJ, Kaidonis JA. Differential wear of teeth and restorative materials: Clinical implications. Int J Prosthodont 2004; 17: 350-356.

29) Suwannaroop P, Chaijareenont P, Kootthathape N, Takahashi H, Arksornmikut M. In vitro wear resistance, hardness and elastic modulus of artificial denture teet. Dent Mater J; 33: 880-894.

30) Ilie N, Hilton TJ, Heintze SD, Hickel R, Watts DC, Silikas N, et al. Academy of Dental Materials guidance—Resin composites: Part I—Mechanical properties. Dent Mater 2017; 33: 880-894.

31) Wesemann C, Spies BC, Sterzenbach G, Beuer F, Kohal R, Wemken G, et al. Polymers for conventional, subtractive, and additive manufacturing of occlusal devices differ in hardness and flexural properties but not in wear resistance. Dent Mater 2021; 37: 432-442.

32) Lassila L, Keulemans F, Vallittu PK, Garoushi S. Characterization of restorative short-fiber reinforced dental composites. Dent Mater J 2020; 39: 992-999.

33) Yildiz Domanci K, Aslan YU, Ozkan Y. Two-body wear of occlusal splint materials against different antagonists. BMC Oral Health 2020; 20: 174.

34) Grymak A, Aarts JM, Ma S, Waddell JN, Choi JJE. Comparison of hardness and polishability of various occlusal splint materials. J Mech Behav Biomed Mater 2021; 115: 104270.

35) Värynen VOE, Tanner J, Vallittu PK. The anisotropy of the flexural properties of an occlusal device material processed by stereolithography. J Prosthodent Dent 2016; 116: 811-817.

36) Patel DR, Sakhaei AH, Layani M, Zhang B, Ge Q. Magdassi S. Highly stretchable and UV curable elastomers for digital light processing based 3D printing. Adv Mater 2017;29: 1606000.

37) Weigel N, Männel MJ, Thiele J. Flexible materials for high-resolution 3D printing of microfluidic devices with integrated droplet size regulation. ACS Appl Mater Interfaces 2021; 13: 31086-31101.

38) Wulf J, Schmid A, Huber C, Rosentritt M. Dynamic fatigue of 3D-printed splint materials. J Mech Behav Biomed Mater 2021; 124: 104885.

39) Grymak A, Waddell JN, Aarts JM, Ma S, Choi JJE. Evaluation of wear behaviour of various occlusal splint materials and manufacturing processes. J Mech Behav Biomed Mater 2022; 126: 105053.

40) Prpić V, Schauperl Z, Ćatić A, Dulčić N, Ćimić S. Comparison of mechanical properties of 3D-printed, CAD/CAM, and conventional denture base materials. J Prosthodont 2020; 29: 524-528.

41) Suzuki S. In vitro wear of nano-composite denture teeth. J Prosthodont 2004; 13: 238-243.

42) Hamanaka I, Takahashi Y, Shimizu H. Mechanical properties of injection-molded thermoplastic denture base resins. Acta Odontol Scand 2011; 69: 75-79.

43) Berli C, Thieringer FM, Sharma N, Müller JA, Dedem P, Fischer J, et al. Comparing the mechanical properties of pressed, milled, and 3D-printed resins for occlusal devices. J Prosthodont 2020; 124: 780-786.

44) Prpic V, Slacanin I, Schauperl Z, Ćatić A, Dulčić N, Ćimić S. A study of the flexural strength and surface hardness of different materials and technologies for occlusal device fabrication. J Prosthodont 2019; 121: 955-959.

45) Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J Prosthodont 2016; 115: 760-767.

46) Alifoi-Segbaya F, Bowman J, White AR, George R, Fidan I. Characterization of the double bond conversion of acrylic resins for 3D printing of dental prostheses. Compend Contin Educ Dent 2019; 40: e77-11.

47) Biron M, et al. Thermoplastic Specific Properties. In: Biron M, editor. Material Selection for Thermoplastic Parts [Internet]. Oxford: William Andrew Publishing; 2016 [cited 2022 Mar 24]. p. 39–75. Available from: https://www.sciencedirect.com/science/article/pii/B9780702062841000027

48) Hamanaka I, Yamamoto M, Lassila LVJ, Vallittu PK, Takahashi Y. Wear resistance of injection-molded thermoplastic denture base resins. Acta Biomater Odontol Scand 2016; 2: 51-57.

49) Negretriu M. Thermoplastic resins for flexible framework removable partial dentures. Timisoara Med J 2005; 55: 295-299.