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MILLED VS. 3D-PRINTED OCCLUSAL DEVICE WEAR CHARACTERISTICS AGAINST ZIRCONIA

by

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ABSTRACT

Milled vs 3D-Printed Occlusal Device Wear Characteristics against Zirconia

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Introduction: Occlusal devices are recommended for patients who have undergone extensive dental treatment, such as full mouth rehabilitation, to protect their restorations and increase their service longevity. With the emergence of Computer-aided design (CAD) and Computer-aided manufacturing (CAM) technologies in dentistry, manufacturing occlusal devices via subtractive or additive methods has mitigated fabrication problems commonly seen in conventional fabrication methods and saves laboratory time. CAD/CAM technology can be utilized to fabricate occlusal devices by milling polymethylmethacrylate (PMMA) or printing resin material using a 3D printer. **Objective**: This *in vitro* study aimed to determine if there are any differences in the amount of wear between milled PMMA and 3D-printed occlusal devices in a simulated one-year usage. **Methods**: Milled PMMA (n=4) and 3D-printed samples (n=4) were subjected to normal wear by cusp-shaped 5Y-TZP zirconia antagonists in a dual-axis chewing machine for 1 year chewing (250,000 loading cycles) simulation. Wear was analyzed by measuring vertical material loss along with rate of wear at every 3-month interval (62,500 cycling). A pairwise comparison t-test was used to compare vertical material loss from two groups. **Results**: Significant differences in the vertical material loss were identified between milled PMMA and 3D-printed samples ($p<.001$). The average vertical losses of PMMA and 3D-printed samples after one year chewing simulation were 0.179 ± 0.047 and 0.384 ± 0.048 respectively. 3D-printed samples continued to wear until 9 months period. PMMA samples initially wore 0.14 mm at 3 months and did not wear significantly thereafter ($p = 0.002$). **Conclusions**: Both PMMA and 3D-printed occlusal devices were capable of withstanding one-year simulated use. Although <5 % vertical material loss of PMMA is remarkable, other factors (e.g., the cost of equipment, materials, and biofilm/hygiene) should also be considered in the decision-making process when selecting materials and methods of fabrication.

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LIST OF ABBREVIATONS

CAD/CAM	Computer-aided design/computer-aided manufacturing
PEEK	Polyetheretherketone
PMMA	Polymethylmethacrylate
5Y-TZP	5 mol% yttria-stabilized tetragonal zirconia polycrystalline

CHAPTER 1: Introduction

Tooth structure wear is routinely observed in the dental practice and is part of the natural aging process.[1] The cause of wear is multifactorial. [2] The loss of tooth structure can occur from erosion, abrasion, or attrition and increases in severity with age. [3] Despite it being a part of the natural aging process, factors such as nocturnal bruxism, parafunctional habits, and/or dietary acids may unnecessarily accelerate this process to progress. The rapid progression of tooth structure loss can be severe and irreparably affect the function and esthetics of people’s dentition.

When severe tooth structure loss occurs, an extensive restorative rehabilitation is warranted. Different combinations of dental materials are used for the restorative process: all-metal, metal-ceramic, and all-ceramic restorations. Ceramic restorations are made from glass ceramics, poly-crystalline alumina, or zirconia. Ceramic usage in dentistry has been expanded with the advancement of CAD/CAM processing technology. [4] Zirconia has strong fracture toughness and wear resistant properties compared to the other dental ceramics. Zirconia is esthetic and allows for minimal tooth preparation designs, which is ideal for extensive rehabilitations. [5, 6] Despite these advantages, zirconia is susceptible to damage from excessive and destructive masticatory forces and parafunctional habits. The American College of Prosthodontists recommends prescribing an occlusal device to protect restorations and increase their service longevity. [7]

There are several options in materials and manufacturing processes used to fabricate occlusal devices. They can be fabricated from soft and flexible materials such as vacuum-formed polymer sheets. Rigid materials, such as auto-polymerized and heat-cured acrylic resins, are also used. The fabrication process of polymer- and resin-based occlusal devices takes place in a dental laboratory or can be performed chairside. Most of these fabrication processes can be time consuming with multiple complex steps, leading to errors and inconsistencies. Additionally, autopolymerizing materials have high polymerization shrinkage, porosities from poorly calculated powder to monomer ratio, and water sorption. [8]

CAD/CAM technologies in dentistry have helped mitigate the potential fabrication problems and errors often seen with the conventional polymer and resin-based occlusal devices. CAD/CAM uses a software enabled intraoral scanner to image and replicate the dentition. The digital scanner saves laboratory time and increases patient comfort, compared to conventional impression techniques and materials. An occlusal device can then be fabricated through either subtractive or additive manufacturing.

Subtractive manufacturing of an occlusal device involves milling a pre-polymerized polymethyl methacrylate (PMMA) blank into a desired shape. An advantage of the process is that there is no shrinkage which negatively affects the conventional auto-polymerizing acrylics. A disadvantage is the higher cost of PMMA blanks. Additive manufacturing, or 3D printing utilizes materials that are relatively lower in cost compared to milling (i.e., subtractive manufacturing). Recently, 3D printing processes have become very accessible and affordable, with many dental practices incorporating them into common use. With the potential economic and laboratory time advantages, the utilization of 3D-printed occlusal devices for patients with multiple zirconia restorations is worth further investigation.

Studies comparing the wear of different materials for occlusal devices have shown that 3D-printed occlusal devices are clinically comparable to those that are milled or conventionally made devices.[8] A systematic review of *in vitro* and *in vivo* studies showed that polyetheretherketone (PEEK) to have the lowest wear compared to heat-polymerized, milled, and 3D-printed materials when used as an occlusal device. The authors found that vacuum-formed materials had the most wear. [9] The authors listed *in vitro* studies that used two-body wear chewing simulators against antagonists such as human enamel, steatite balls, tungsten carbide, stainless steel, lithium disilicate or zirconia. The authors found that there were limited studies with 3D-printed occlusal devices and advocated that more studies of these occlusal devices were necessary. [10]

The purpose of this study was to investigate the wear characteristics of occlusal devices fabricated by subtractive and additive techniques against 5Y-TZP zirconia. 5Y-TZP is a 5 mol% yttria-stabilized tetragonal zirconia polycrystalline and was selected for this study due to its translucent incisal zone. This translucency provides restorations that can be used as both posterior and anterior restorations that are highly esthetic. The null hypothesis proposed was there would be no significant difference in wear characteristics between milled and 3D-printed occlusal devices.

CHAPTER 2: Materials and Methods

Methods are partly based on previous NPDS resident's USUHS thesis. [11]

CAD/CAM software (exocad, exocad GmbH, Darmstadt, Germany) was utilized to design cusp-shaped antagonist abraders, featuring a slightly conical artificial cusp with a round tip measuring 2 mm in diameter. These designs served as templates for creating standard antagonists using the restorative material listed in Table 1. Zirconia antagonists (IPS e.max ZirCAD Prime, Ivoclar Vivadent, Liechtenstein) were milled using a 5-axis mill (CORiTEC 150i, imes-icore, Eiterfeld, Germany).

The zirconia antagonists underwent sintering and polishing processes before being placed in the antagonist holder of the Chewing Simulator-4 (SD Mechatronik, Westerham, Germany). The translucent portions (5Y-TZP) of the zirconia cusps were in contact with the samples while the chewing simulation was conducted. A total of 250,000 chewing cycles were applied to each sample, with a loading frequency of 1.6 Hz. The chewing simulator subjected the samples to a vertical force of 49N, accompanied by horizontal sliding of 0.7 mm and separation. Detailed parameters for the chewing simulator are listed in Table 2.

Two commonly used occlusal device materials were chosen to represent subtractive (milled) manufacturing, and additive (3D printing) manufacturing methods. Table 3 lists these materials and their compositions. Samples (n=4) of each material (8 total samples) were designed on exocad along with a custom sample holder in the shape of three teeth (#14,15 and 16) scanned from a typodont depicted in Figure 3. Both sample materials were designed with a thickness of 2mm.

Milled samples of polymethylmethacrylate (PREMIOtemp Mono, primotec, Bad Homburg, Germany) were fabricated using a 5-axis milling unit (CORiTEC 150i, imes-icore, Eiterfeld, Germany) as shown in Figure 4a. Stereolithographic (SLA) 3D printing (Formlab Form 3B+, Dental LT Clear, Somerville, Massachusetts) was employed to create 3D-printed samples shown in Figure 4b. Both samples were subsequently polished using acrylic polishing burs, pumice, and high shine. The samples were mounted on a custom 3D-printed sample holder shaped like three teeth and placed within the chewing simulator (Chewing Simulator-4, SD Mechatronik, Westerham, Germany; Fig 3). To conduct a two-body wear test, the sample materials were subjected to antagonist abraders on the chewing simulator. The maximum vertical wear of the samples was quantified by utilizing a model scanner (Freedom HD, DOF, Seoul, South Korea) and 3D modeling software (Materialise 3-matic Medical version 16.0, 3DZ Group, Malta). A three-dimensional mesh was obtained from the model scanner and imported into the 3D modeling software. Indentation depth was determined by measuring the radii of two circles as shown in Figure 1. The first circle, denoted as C_1, was fitted to the edge formed by the intersection of the indentation and the sample surface. The second circle, denoted as C_2, was fitted to the apex of the indentation and two points along C_1 that were perpendicular to the sample surface. The depth of the indentation was determined using a methodology based on the relationship between the two circles.

Using a conventional coordinate system with the origin at the center of C_2, the Y coordinate was determined given its associated X location and the radius of the circle by rearranging Equation (1) to Equation (2):

Equation of C_2:

$$(X_2-H_2)^2 + (Y_2-K_2)^2 = R_2^2 \tag{1}$$

Assuming the center of the circle is at (0,0) and solving for Y_2

$$Y_2 = \mathrm{sqrt}(R_2^2 - X_2^2) \tag{2}$$

Since C_1 and C_2 intersect where C_1 passes through the surface of the sample, equation (2) can be used to calculate the Y location of the sample surface. Substituting equation (2) into equation (3) allows for the determination of indentation depth using the radius of both circles.

$$\Delta H = R_2 - Y_2 \tag{3}$$

$$\Delta H = R_2 - \mathrm{sqrt}(R_2^2 - R_1^2) \tag{4}$$

A pair-wise t-test was conducted to compare the mean vertical loss between the two occlusal device samples.

CHAPTER 3: Results

In this *in vitro* study, the wear characteristics of occlusal devices fabricated by subtractive and additive techniques against 5Y-TZP zirconia were examined. The vertical material loss results are presented in Table 4, with corresponding mean values listed in Table 5. Figure 2 displays a box and whisker plot of the average vertical loss for four milled PMMA samples (shown in turquoise) and four 3D-printed samples (shown in red) over 12 months of simulated use. The y-axis represents the mean vertical loss in millimeters, while the x-axis displays the duration in 3-month equivalent chewing intervals.

Significant differences in vertical material loss were observed between PMMA and 3D-printed samples (Pairwise t-test; $p<.001$) as depicted in Figure 2. There were no significant differences between milled samples across all time points in Table 5 (p-value: 0.593). However, significant differences exist between time points for the 3D-printed samples (p-value: 0.002). For the 3D-printed samples, the mean vertical loss values ranged from 0.253mm at 3 months to 0.048mm at 12 months. The standard deviation was 0.048mm. In comparison, the milled samples exhibited mean vertical loss values ranging from 0.144mm at 3 months to 0.179mm at 12 months, with a standard deviation of 0.047mm.

It can be observed that the mean vertical loss increased with duration for both 3D-printed and milled PMMA samples. At each duration, the 3D-printed samples generally exhibited higher mean vertical loss values compared to the milled PMMA samples. Notably, the 3D-printed samples continued to experience wear until the 9-month mark, whereas milled PMMA exhibited an initial wear of 0.14 mm at 3 months but did not exhibit significant wear thereafter ($p = 0.002$). These findings suggest that the 3D-printed and milled PMMA samples undergo vertical loss and wear over time, with the 3D-printed samples generally exhibiting higher values.

CHAPTER 4: Discussion

Occlusal devices serve multiple purposes ranging from alleviating symptoms of temporomandibular disorders, bruxism, and protecting teeth or restorations from wear. With the advances in CAD/CAM technology, dentists have the option to select between milled and 3D-printed manufacturing methods when fabricating occlusal devices. This study aimed to compare the wear behaviors of milled PMMA, and 3D-printed occlusal devices after simulated one year of use.

The findings of this study indicate that both milled PMMA and 3D-printed occlusal devices can be used effectively for up to a year without requiring replacement. At the one-year mark, the mean vertical wear observed was well below the initial sample thickness of 2 mm for both samples, with milled samples exhibiting a mean wear of 0.179 mm (8.95 %) and 3D-printed samples showing wear of 0.384 mm (19.2 %). Statistical analysis revealed the degree of apparent wear was significantly lower in the milled samples compared to 3D-printed samples, therefore the null hypothesis was rejected. However, the clinical significance of the observed wear and wear rate seemed negligible since both milled, and 3D-printed occlusal devices show that they can potentially be in service for many years (approximately 9 and 3.5 more years for milled and 3D-printed occlusal devices respectively assuming 90% wear at the endpoint). Thus, material and manufacturing modality election based on cost and time efficiency may be of more significance than material wear resistance.

The results from this study are consistent with previous studies that have suggested milled occlusal devices generally have higher wear resistance than 3D-printed devices.[9, 10, 12] The reasons for the differences in the wear resistance could be attributed to factors such as material properties, manufacturing processes, and surface finish.[13, 14] Milled PMMA occlusal devices are produced by milling a solid blank of pre-polymerized PMMA. This solid blank of pre-polymerized PMMA results in a denser final product with fewer voids and defects compared to the layered structure of 3D-printed devices.[13] A study comparing the wear of milled and 3D-printed samples against metal abraders found cracks and flaws in the 3D-printed samples due to separation of the inter-layer bonds which resulted in weaker 3D-printed devices compared to the milled devices.[8] Apart from material properties and manufacturing processes, it should be noted that milled PMMA devices have a smoother surface finish compared to 3D-printed devices.[15]

There are several limitations to this study. The current study used the mean vertical loss to approximate the actual mean volume loss. The approximation depends on the wear pattern being a sphere shape. Secondly, one type of 3D printer resin was tested. There is a possibility that other resins may have better material properties than the one tested in this study.

Future research should carefully evaluate the performance of various 3D printer resins and next generation 3D printers in CAD/CAM-manufactured occlusal devices. An *in vivo* study should confirm the wear rates found in this study.

CHAPTER 5: Conclusions

The results of this study indicate that both milled PMMA and 3D-printed occlusal devices can withstand one year of simulated use, as evidenced by their wear pattern and wear rate. However, the milled PMMA occlusal device outperformed the 3D-printed device in terms of vertical loss, suggesting that the former may be a superior choice for long-term use. It is important to note that this study had certain limitations, including measuring vertical loss and the use of only one type of 3D printer resin material. Future studies should aim to address this limitation by testing various types of resin and post-processing techniques. Additionally, it would be valuable to establish a clinically acceptable wear rate for these occlusal devices before replacement is necessary. Such research could inform the development of more durable and effective occlusal devices for clinical use.

Table 1. Antagonist material.

Material	Product	Manufacturer
Zirconia (5Y-TZP)	IPS e.max ZirCAD Prime	Ivoclar Vivadent, Liechtenstein

Table 2. Chewing simulator parameters.[11]

Parameter	**Data**
Number of cycles	250,000
Force	49 N
Height	2 mm
Lateral movement	~0.7 mm
Descendent speed	60 mm/s
Lifting speed	60 mm/s
Feed speed	40 mm/s
Return speed	50 mm/s
Frequency	1.6 Hz

Table 3. Occlusal device material samples with 2mm thickness.

No.	Material	Manufacturer	Method	Composition
1	PREMIOtemp Mono	Bad Homburg, Germany	Milled	Polymethylmethacrylate (PMMA)
2	Dental LT Clear	Formlab Form 3B+, Somerville, Massachusetts	3D-printed	Photoreactive Resin (Proprietary Ingredient)

Table 4. Vertical loss measurements following chewing simulation (in millimeters).

	Number of Cycles											
	62500			125000			187500			250000		
Sample ID	C_1	C_2	Depth	C_1	C_2	Depth	C_1	C_2	Depth	C_1	C_2	Depth
3D Resin 1	0.93	1.83	0.254	1.02	1.68	0.345	1.03	1.56	0.388	1.03	1.57	0.385
3D Resin 2	0.88	1.88	0.219	1.05	2.04	0.291	1.02	1.65	0.353	1.07	1.50	0.449
3D Resin 3	0.96	2.01	0.244	1.03	1.88	0.307	1.09	1.38	0.534	1.08	1.78	0.365
3D Resin 4	0.85	1.37	0.296	0.97	1.78	0.288	0.97	1.37	0.403	0.97	1.57	0.335
PMMA 1	0.89	2.69	0.151	0.85	1.71	0.226	0.71	1.78	0.148	0.86	1.61	0.249
PMMA 2	0.65	1.65	0.133	0.82	2.41	0.144	0.89	2.49	0.164	0.82	2.30	0.151
PMMA 3	0.80	1.93	0.174	0.76	1.68	0.182	0.89	1.63	0.264	0.81	2.25	0.151
PMMA 4	0.62	1.63	0.123	0.64	1.97	0.107	0.65	1.32	0.171	0.67	1.45	0.164

Table 5. Mean vertical loss comparisons following chewing simulation (in millimeters).

Duration	**3D-printed**	**Milled PMMA**
3 months	0.253	0.144
6 months	0.308	0.165
9 months	0.419	0.187
12 months	0.048	0.179
SD	0.048	0.047

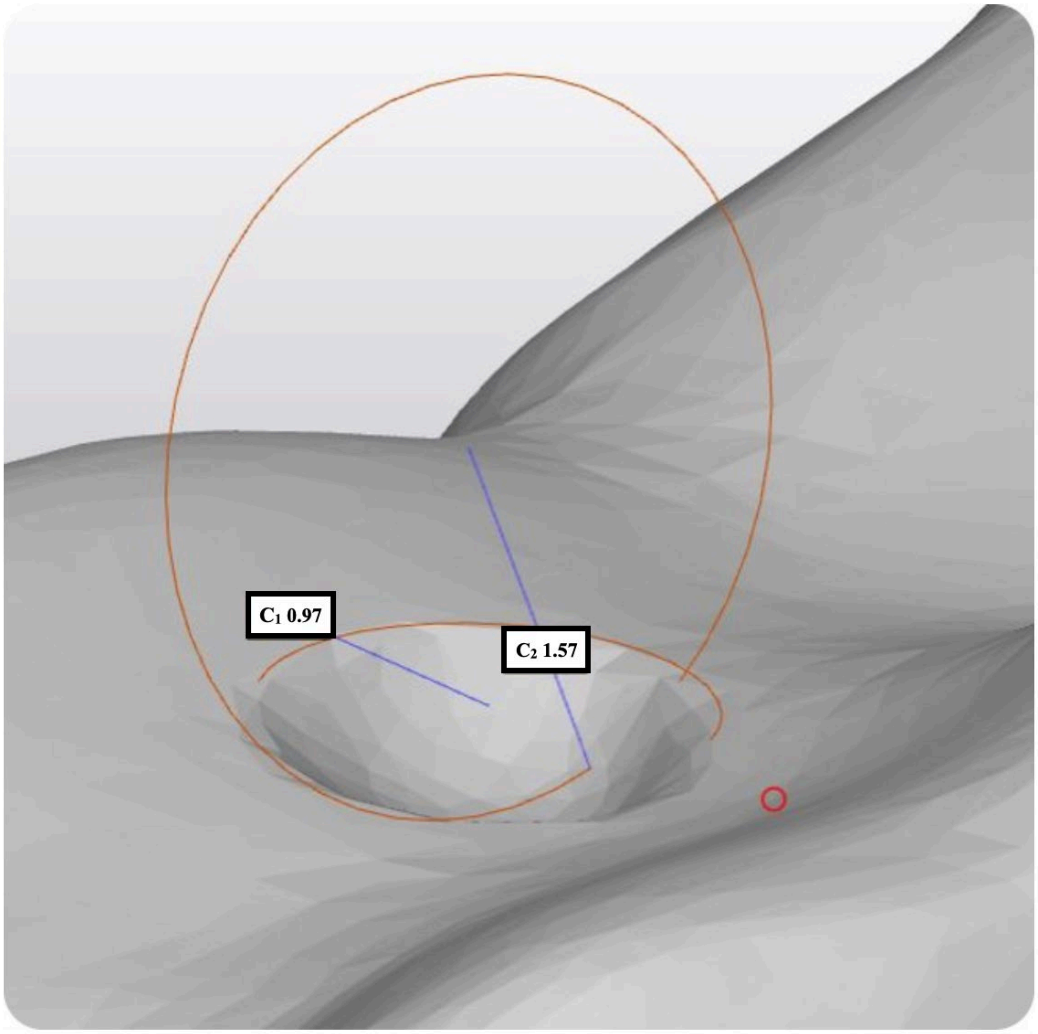

Figure 1. Digital image displaying the depth of simulated chewing-induced wear indentation. Indentation depth was measured by using the radii of circles C1 and C2. The numbers in this figure represent the measured radius in millimeters (mm). C1 denotes the radius of the circle formed at the intersection of the sample surface and the indentation. C2 denotes the radius of the larger circle positioned at the deepest point within the indentation, connecting with two points along C1 that are perpendicular to the sample surface.

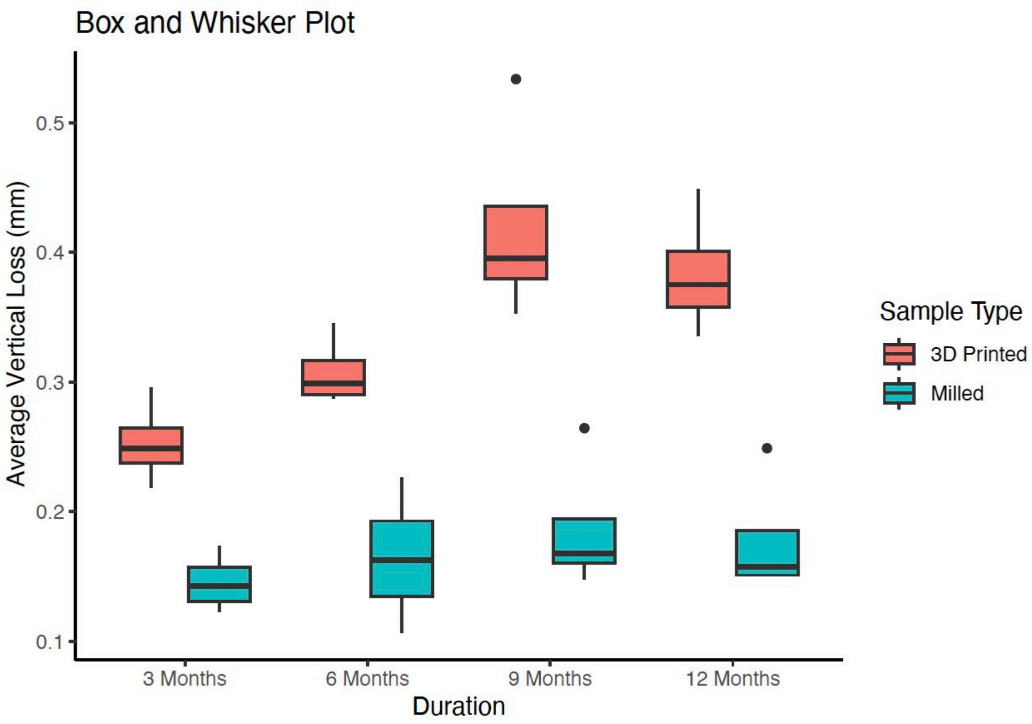

Figure 2. Box and whisker plot that is grouped by time point and visualized by sample type. The y-axis of the graph represents the average vertical loss in millimeters (mm), while the x-axis represents the duration in 3-month equivalent chewing intervals. The graph includes red boxes indicating four 3D-printed samples and turquoise boxes representing four milled PMMA samples.

Figure 3. Image of 3D-printed custom sample holder. 3D-printed custom sample holder fabricated from a scan of typodont teeth #14, 15, and 16, designed on exocad software.

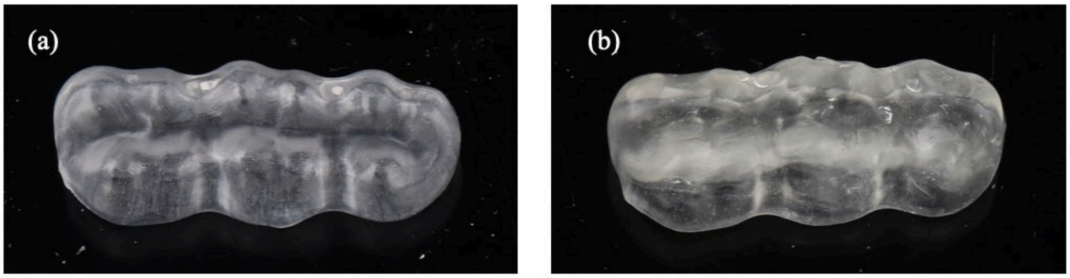

Figure 4. Occlusal device samples. (a) Milled PMMA sample, and (b) 3D-printed sample.

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