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Flexural Strength of 3D Printed Denture Acrylic Compared to Conventional and Milled Denture Acrylic.

A manuscript

Presented to the Faculty of the Advanced Education in General Dentistry, Two-Year Program,

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And the Uniformed Services University of the Health Sciences – Post Graduate Dental College

In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Oral Biology

By

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Abstract

Flexural Strength of 3D Printed Denture Acrylic Compared to Conventional and Milled Denture Acrylic.

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Introduction: Denture base acrylics have been made of ivory, wood and rubber before polymethyl methacrylate (PMMA) was utilized in the 1940's. Since PMMA is the material of choice for denture bases for esthetics and physical properties, manufacturers have attempted to create and improve PMMA with different fabrication methods. There are heat-activated and auto-polymerized PMMA's as well as newer milled, injection molded and 3D printed methods.

Objective: Compare the flexural strength and flexural modulus of three commercially available denture bases with a three-point bend test on ISO-standard bars. 3D printed PMMA (Denture Base Resin LP, Formlabs), Milled PMMA (Ivotion Base, Ivoclar Vivadent), and conventional heat polymerized PMMA (Lucitone 199 Hybrid, Dentsply Sirona). The null hypothesis is there is no difference in the flexural strength of the three tested materials.

Methods: 30 PMMA bars split evenly in three groups by production method were fabricated in ISO-standard size of 64 x 10 x 3.3 mm. After processing, the bars were shaped, polished and measured. Samples were stored in 37-degree Celsius water for 1 week. Following completion samples were subjected to a three-point flexural test by the MTS 858 Mini Bionix II and the resulting data was used to measure flexural strength and flexural modulus.

Results: Based on an analysis of variance test, it was revealed that the flexural strength of conventional (M = 72.57 MPa; SD = 7.35) and milled samples (M = 73.13 MPa; SD = 2.57) did not differ (P=0.97). However, the 3D printed samples were found to have a 30% higher mean flexural strength (M = 95.06 MPa; SD = 3.60) compared to conventional and milled samples, both P<0.001. Similarly, the calculated flexural modulus of conventional (M = 495.76; SD = 75.76) and milled samples (M = 509.28; SD = 79.34) did not differ significantly, P=0.90.

Conclusion: All three of the PMMA fabrication methods produced denture base materials that passed a threshold for use regarding flexural strength. However, it was found that 3D printed samples of Formlabs Denture Base Resin LP had a higher flexural strength and flexural modulus compared to the other two groups. This shows 3D printed materials have a bright future denture bases of the future.

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ANOVA – Analysis of Variance

ISO – International Organization for Standardization

PMMA – Polymethyl Methacrylate

BACKGROUND:

Dentures have been fabricated by the Etruscans of Tuscia as early as 700 BC[12]. These dentures were made of a combination of ivory, bone and natural teeth. Sometimes teeth would be held in place by gold wires, bands, or rivets if multiple materials were used. During a similar timeframe, the Japanese would carve out dentures from box and cherry wood. Natural teeth were fixed into place with screws within the wood. This was a problem as the denture bases warped and cracked from saliva, and other general wear and tear[4]. In the 16th century Pierre Fauchard carved entire dentures out of a single piece of ivory or bone. These provided better dimensional stability but were unacceptable regarding esthetics and retention. The next breakthrough was the invention of an impression technique where impressed pieces of wax were poured up in plaster. French dentists utilized this method to create gold denture bases. The gold would be designed with holes where teeth shaped from ivory could be placed within and fixated into place with pins[12].

In the 1850's denture bases had evolved into other materials like porcelain and vulcanite. The porcelain denture was exceptionally difficult to fit on the patient due to the dimensional change that occurs when porcelain is fired. The rubber, called Vulcanite, from Charles Goodyear was an exceptional revolution and provided a cost effective, comfortable, and durability to denture bases. After vulcanite was patented, dentists were forced to use other methods and tried gutta percha, aluminum, and cheoplasty[3]. As the physical properties of these denture bases were becoming more predictable, increasing the esthetics of dentures was able to become more of a priority.

The modern denture base has been utilizing increasingly stronger and esthetic denture bases since the 1940's called polymethyl methacrylate (PMMA). PMMA has superior physical properties consisting of high mechanical strength, modulus of elasticity, dimensional stability, and low water solubility. It was estimated that by 1946 95% of all dentures were fabricated using PMMA polymers[10]. Once fabricated, the denture can be customized and adjusted easily to become a very esthetic final product.

There are several methods to fabricate denture bases with acrylic. Polymethyl methacrylate was originally heat polymerized but soon after auto-polymerized resins were introduced. Both methods have been used for decades with success with PMMA denture bases. Today, there are several viable methods for fabricating PMMA. Injection molding of PMMA by special machines to at the exact time and temperature, milling from pre-polymerized pucks, conventional means using flasking with pressure and heat, and most recently 3D printing. Studies have been done on the flexural strength of most materials, however, there is still a need for more studies to determine how well the physical properties of additive manufactured PMMA holds up compared to others. If this material is capable of the physical properties necessary to withstand the forces encountered in an intraoral environment, then this workflow could significantly shift the preferred methods of fabrication.

METHODS AND MATERIALS:

Three groups of 10 PMMA samples were be fabricated to ISO-compliant rectangular shape and size of 64 x 10 x 3.3 mm. The three groups were the following materials: the conventionally fabricated PMMA was Lucitone 199 (Dentsply Sirona, Charlotte, NC), the milled material was Ivotion Base, (Ivoclar Vivadent, Schaan, Liechtenstein), and the 3D printed material was Denture base Resin LP (Formlabs, Somerville, MA).

A Formlabs 3B+ 3D printer was be used to fabricate 10 bars of PMMA. The ten samples were printed simultaneously after an STL was designed with Tinkercad (Autodesk, San Francisco, CA) to the exact size. Immediately after printing the bars were placed in an isopropyl alcohol bath for 10 minutes. Two heat curing cycles of 30 minutes at 80 degrees Celsius completd the post-processing of this material[8,9]. Supports were clipped with the removal shears.

Figure 1: Isopropyl alcohol bath for Intraoral printed resin models

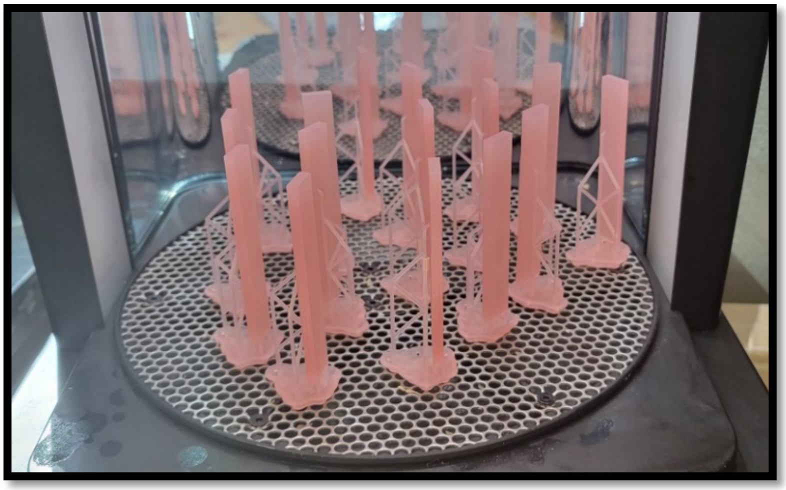

Figure 2: Denture Base LP after second 30-minute cure

Figure 3: Denture base LP ready for testing

A CORiTEC 350i (imes-icore GmbH, Hessen, Germany) was loaded with a prepolymerized PMMA puck of Ivotion base. The same STL from Tinkercad was nested within the Hyperdent program (FOLLOW-ME! Technology Group, Munich, Germany) and three bars were milled out in one cycle. After 10 bars were milled the sprues were removed and ready for testing.

Figure 4: 98.5 x 30 mm Ivotion Base puck ready to be milled

Figure 5: 350i 5 axis mill custom dry milling the bars

Figure 6: Finished bars immediately following milling

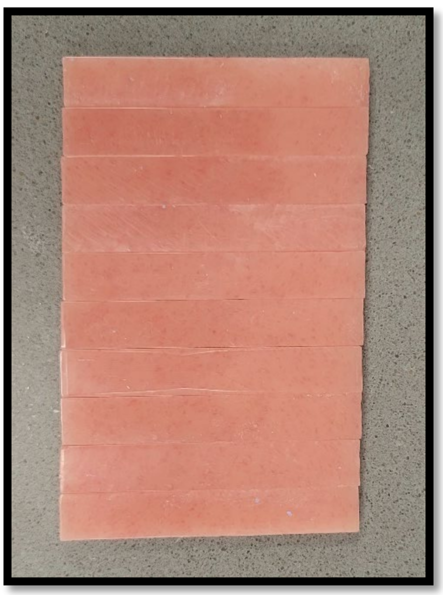

Figure 7: Ivotion Base ready for testing

In order to fabricate the conventional bars, the correct template needed to be created. For the sake of accuracy, wax bars were milled to previously described ISO standard. Samples were flasked and invested with type 3 dental stone mixed in a vacuum mixer. The wax bars completed a boil out cycle for 10 min with boiling water and the flasks were flushed with hot water, separated and allowed to cool to room temperature. The stone was generously coated with APS separator and Lucitone 199 Hybrid was hand packed and condensed into the mold. Two trial packs with a plastic separator in a Nevin 832 Denture Flask Press (SPW Industrial, Laguna Hills, Ca) were used to pack sufficient PMMA within the templates. Excess PMMA was cut away until the template shape was replicated. The final close was completed on each flask. Flasks were placed into a spring clamp follwed by submersion into an E2 Washing and Polymerizing Machine (Mestra, Spain) on the long cycle, which is set at 60-70 degrees Celsius for 9 hours. After the flasks were removed from the water they were allowed to cool and the samples were retrieved.

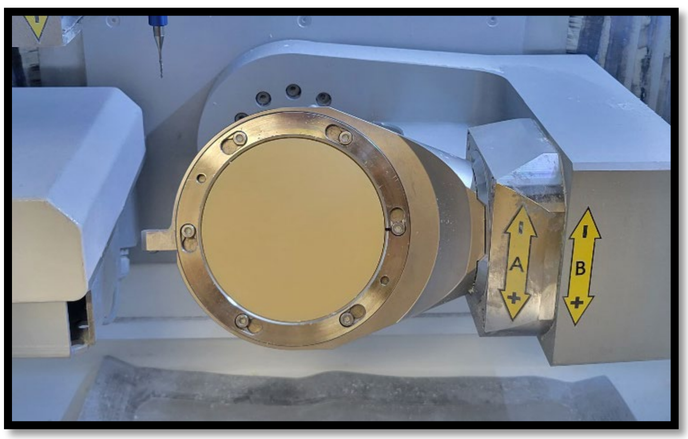

Figure 8: 98x16 wax puck from ImagineUSA


Figure 9.1 and 9.2: Wax bars fully seated in type 3 stone. Fully flasked PMMA in stone

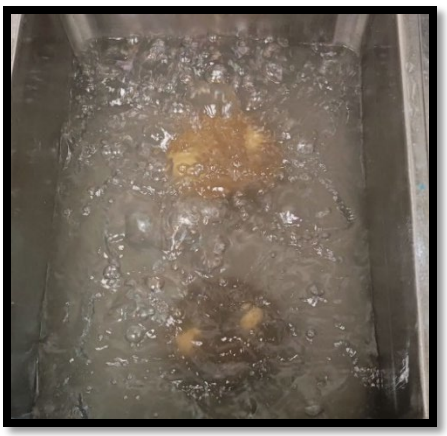
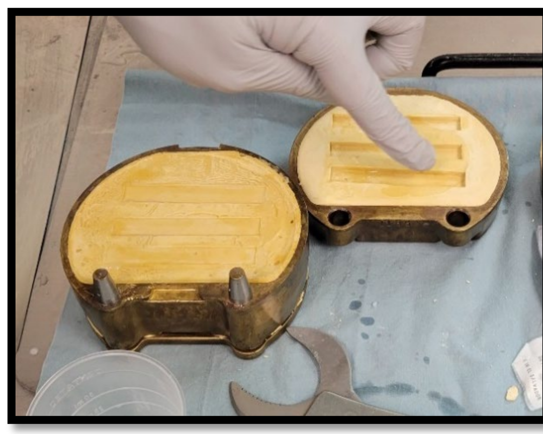

Figure 10.1 and 10.2: Wax boil out. Flask separated to reveal stone template for PMMA


Figure 11.1 and 11.2: Mixing of Lucitone 199. Hand packing of PMMA.

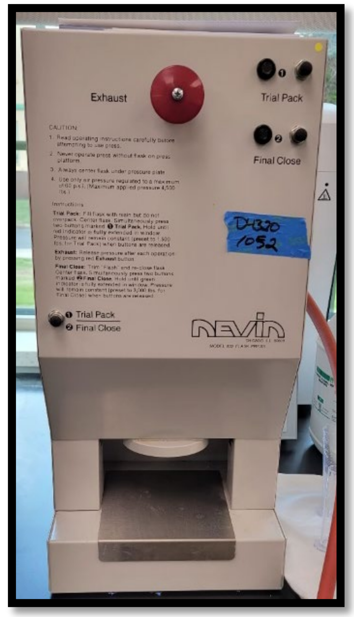

Figure 12.1 and 12.2: Condensing of PMMA. Nevin 832 Denture Flask Press

Figure 13.1 and 13.2: Closing of flask system. Deflasked PMMA

Figure 14: Lucitone 199 ready for testing

The 30 samples were shaped as needed, polished and measured with an Absolute AOS digital caliper (Mitutoyo, Japan). Samples were stored in 37-degree Celsius water for 1 week to simulate an oral environment. Samples were subjected to a three-point flexural test by the MTS 858 Mini Bionix II and the resulting force at fracture was used to measure flexural strength and flexural modulus. The mechanical testing was completed at the Department of Clinical Investigation on the Tripler Army Medical Center's campus.

Figure 15: Measurements of PMMA Samples

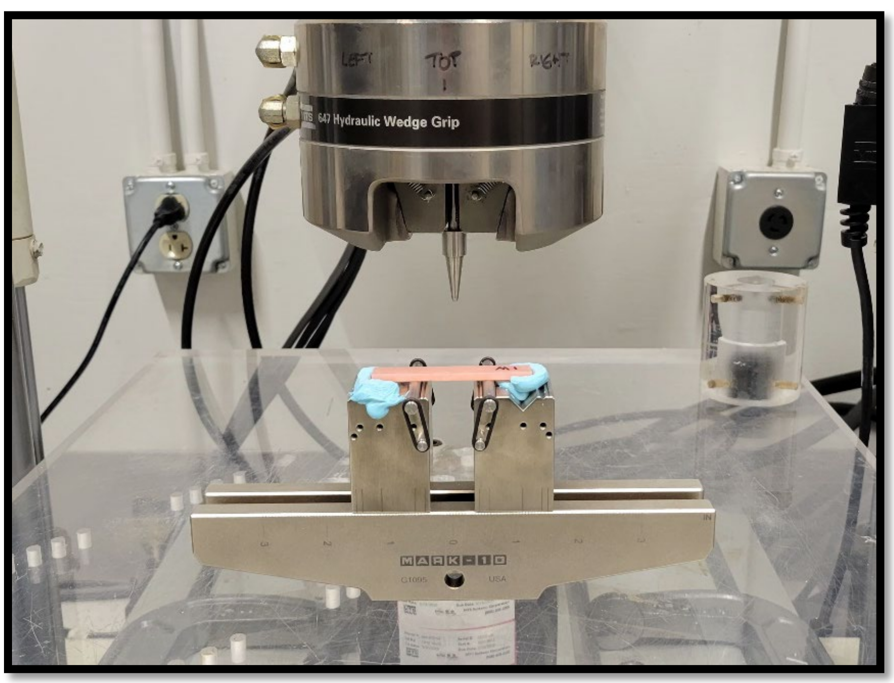

Figure 16: MTS858 Mini Bionix II Tensiometer with prepared sample

Data was recorded and analyzed using a a one-way analysis of variance (ANOVA) followed by post hoc pairwise testing. Based on 10 samples per group (3 groups - conventional, milled, and 3D printed) and letting alpha = 0.05, the study had 90.5% power to detect a difference of 25% among treatments in measures such as flexural strength and flexural modulus assuming a standard deviation of 15% of the mean.

The formula used for flexural strength is $3PL/2bd^2$ and for flexural modulus $PL^3/4Ybd^3$. The maximum load right at failure was be designated as P in newtons, Y was the recorded deflection from initial contact of the bar by the tensiometer up until the failure point. The other variables are specimen width (b), Span length (L) which was 24mm, and specimen thickness (d).

RESULTS:

Data was screened for normality using the Shapiro–Wilk statistic. Consequently, measures of central tendency and dispersion are reported as means with associated standard deviations. The ANOVA was used to examine differences with respect to flexural strength and flexural modulus between the three groups. Eta squared (η^2) statistics are presented as measures of effect size for significant results. Significant results were further explored using A value of $P < 0.05$ was considered significant for all tests. All data were analyzed with the IBM SPSS version 25 (IBM Corporation, Armonk NY, USA)[6].

A total of 30 assessed samples evenly split between conventional, milled, and 3D printed denture acrylic were tested for this study. Table 1 shows the mean flexural strength and modulus of the samples by group. The analysis of variances revealed a large difference in terms of both flexural strength ($P < 0.001$, $\eta^2 = 0.83$) and flexural modulus ($P < 0.001$, $\eta^2 = 0.80$).

Based on follow-up analyses using Tukey's post-hoc test, it was revealed that the flexural strength of conventional (M = 72.57 MPa; SD = 7.35) and milled samples (M = 73.13 MPa; SD = 2.57) did not differ (P=0.97). However, the 3D printed samples were found to have a significantly higher mean flexural strength (M = 95.06 MPa; SD = 3.60) compared to conventional and milled samples, both P<0.001. Similarly, the calculated flexural modulus of conventional (M = 495.76; SD = 75.76) and milled samples (M = 509.28; SD = 79.34) did not differ significantly, P=0.90. Again, the 3D printed samples showed the highest values with a mean flexural modulus of 774.22 (SD = 4.84), both P<0.001.

Material Type	**N**	**Flexural Strength, M (SD)**	**Flexural Modulus, M (SD)**
Conventional	10	72.57 MPa (7.35)	495.76 MPa (75.76)
Milled	10	73.13 MPa (2.57)	509.28 MPa (79.34)
3D Printed	10	99.37 MPa (3.60)	827.96 MPa (44.84)

Table 1: Mean Flexural Strength and Modulus in MPa

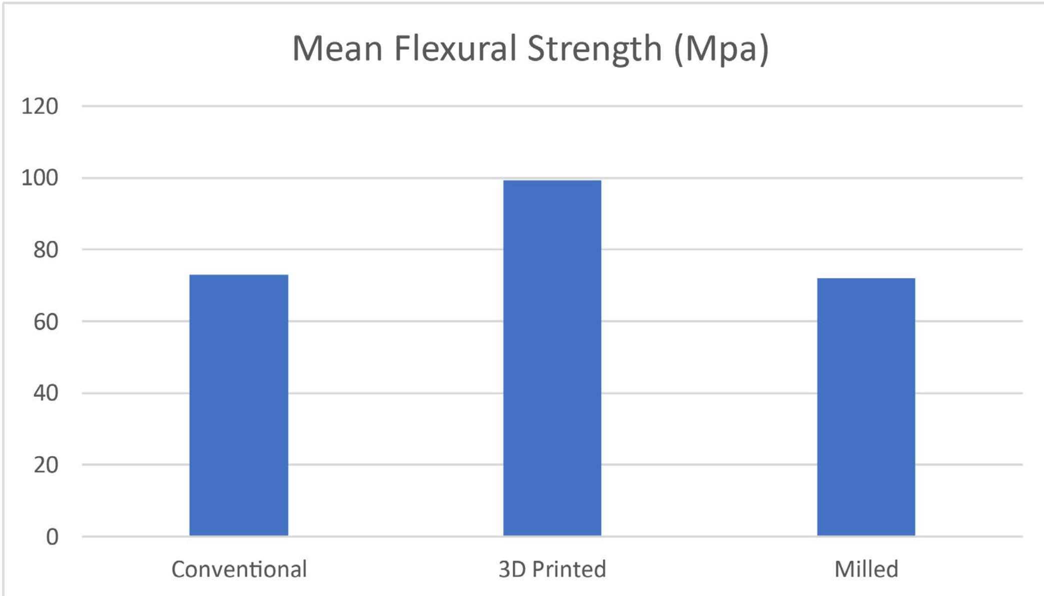

Figure 17: Mean Flexural Strength of PMMA bars in MPa

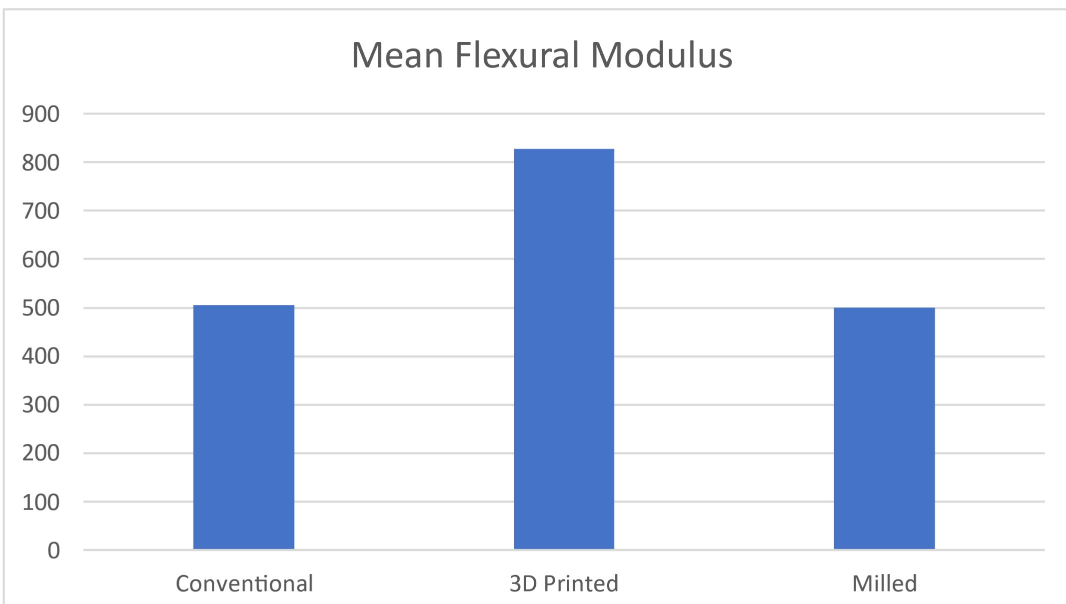

Figure 18: Mean Flexural Modulus of PMMA bars in MPa

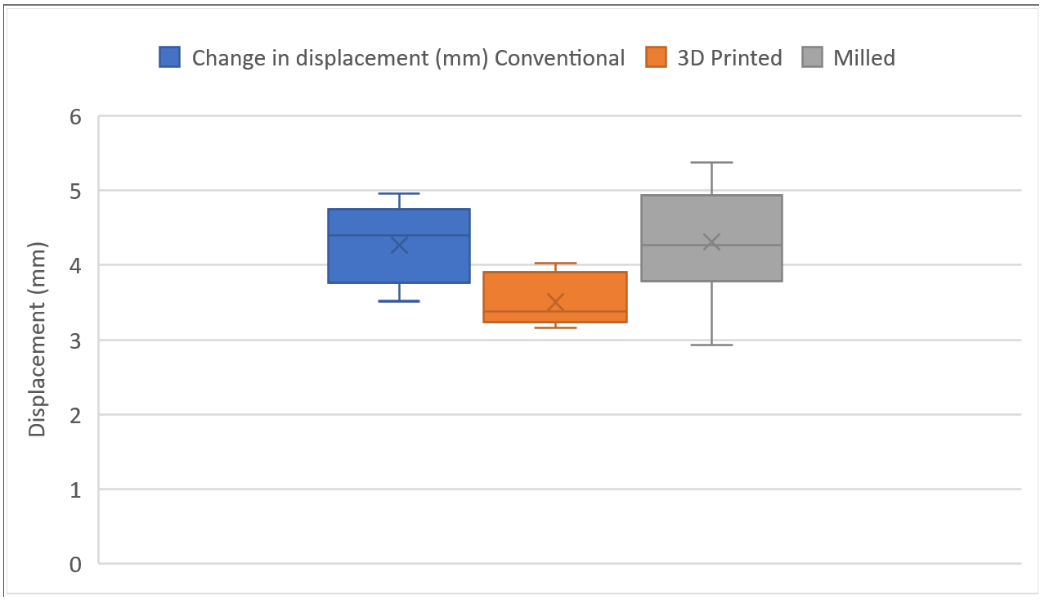

Figure 19: Change in displacement PMMA

DISCUSSION:

The flexural strength according to EN ISO 20795-1 indicates the value of the flexural tension that is present when a test specimen is loaded to the maximum. The standard for self-curing polymers states that the value must be at least 60 MPa. The standard for heat-curing polymers must be at least 65 MPa (ISO standard 1567). The materials tested within this study easily passed those benchmarks. That corroborates the manufacturer's recommendations from their internal studies that they are satisfactory for commercial practice. During the fabrication of the bars, the conventional were the most difficult to create at the correct dimensions. This ultimately led to more grinding and polishing of the bars that the other fabrication methods didn't have need of due to their accuracy. This should be noted as a possible factor for the conventional PMMA to have altered physical properties.

The higher the flexural modulus, the more force is required to achieve a certain elastic deformation. For this parameter, values of more than 1500 MPa (self-curing polymers) and 2000 MPa (heat-curing polymers) are required. In this study, the flexural modulus reached was not sufficient to pass these benchmarks. The suspected explanation was based in the inability to create our own program to run the tensiometer. In other studies, focused on the flexural modulus, the crosshead speed, or the speed that the force is placed on the sample was 5mm/min. In our study we used a crosshead speed of 1mm/min. In a study from Singer et al. it was shown that the flexural modulus is significantly increased by about 10-15% when crosshead speed is doubled [14]. This finding would lead us to fabricate an additional test where we complete the same project with a crosshead speed of 5mm/min.

The goal of this study was to investigate the different physical properties present within PMMA due to different fabrication methods. However, patients are very interested with the appearance of the denture as well. It doesn't matter how superior in strength a denture is if the patient won't wear it. Acrylic stains and glazes are on the market that can make almost any PMMA look esthetic with the right technician and time. Nevertheless, there are a multitude of different shades, translucencies, and styles to choose from right out of processing, and some dentures may not receive much, or any, additional beautification post processing. This could be due to manufacturer experience, comfort level, or price point of the denture that they are fabricating. Therefore, looking at the esthetics immediately following their processing is valuable. The Ivotion base had a reasonably translucent pink with streaks of red to simulate capillaries and blood flow. The Lucitone 199 was a solid color that would blend well with gingiva; however, it was not very translucent. The Formlabs Denture Base Resin LP was extremely translucent but not very esthetic. This material would arguably require the greater artistic touch to make it look natural.

The conventional PMMA was the most time consuming and complicated to produce. You are required to have stone, analog waxing capabilities, flasks and spring coils. You need large appliances that can condense and heat cure your flasks. However, the Lucitone 199 itself is cheap and can be used for several dentures. The milled product is extremely expensive to produce locally at the clinic. The mill itself will cost hundreds of thousands of dollars and the PMMA pucks are $300-400. There is also sensitive maintenance, expensive burs, and wasted PMMA from the puck. This is a complicated fabrication method that requires a strict cost analysis to see if it would be feasible in an office, especially a military clinic, and be profitable. The 3D printed method has a significantly smaller footprint and requires minimal training to produce. You require a printer that is the size of a microwave, and an alcohol bath and thermal curing system that are each the size of a toaster. This will ultimately increase a clinics or dentist's ability to fabricate a denture anywhere there is a power source and a computer with the printer system.

CONCLUSION:

The flexural strength and flexural modulus were significantly higher with the 3D printed PMMA from Formlabs compared to the other two. While it wasn't the most esthetic, the 3D printed method of fabrication is just now gaining momentum within the manufacturing and dental world. This leads dentists, and especially Army dentists, to be confident that the future is bright and this technology can be a game changer for the profession. Ultimately, material researchers need to focus efforts on testing these materials often to bring 3D printing mainstream to a clinic near you.

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