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COMPARATIVE LABORATORY INVESTIGATION FOR THE EFFECT OF THERMO-MECHANICAL STRESSES ON MANDIBULAR DENTURE BASE DEFORMATION FOR 3D PRINTED AND CONVENTIONAL DENTURES

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ABSTRACT

The purpose: This in-vitro study aimed to analyze and compare the effect of thermo-mechanical stresses on mandibular denture base deformation for three-dimensional dentures printing (3D printing) compared to those fabricated by conventional processing techniques with different arch forms (square, ovoid and tapering).

Materials and methods: A total of 30 mandibular denture bases were fabricated, they divided according to the technique of denture construction into two main groups; GI: Mandibular dentures constructed by additive manufacturing technique, GII: mandibular dentures constructed using water bath curing method, each group was sub-divided according to the arch form into three equal sub groups (square, ovoid and tapered). The bases were subjected to thermo-mechanical cycling. Deformation was verified by superimposing the output of each STL file of the scanned mandibular dentures prior and following thermo-mechanical cycling procedure. Data were statistically analyzed.

Results: One Way ANOVA test was used to compare more than 2 independent groups and Two Way ANOVA test was used to compare effect of combined independent factors on single continuous parametric outcome. Higher mean deformation was found in favor to the square arch Form, with statistically significant difference in GI. For the combined effect of deformation, there was statistically significant effect on deformation of complete denture in favor to GI .

Conclusion: Supporting on the results of this research, it might be terminated that increased deformation was found for the 3d printed denture bases rather than the conventional heat-cured group. Moreover square arch forms introduced higher deformation values for both groups.

KEYWORDS: Thermo-mechanical stresses, deformation, 3d printing, mandibular dentures, heat-cured.

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INTRODUCTION

For people who are entirely edentulous, a complete denture is one of the most popular treatment options. Although dental implants have provided an alternative to complete dentures, the therapy's complexity, surgical requirements, and financial load make complete dentures an unavoidable treatment option for many patients. (1)

The most prevalent denture base material is acrylic resin polymethylmethacrylate (PMMA). PMMA resin is the best choice for a denture base material because it fulfills all of the requirements. Its benefits range from ease of repair to a pleasing appearance and a cheap price. Polymerization is initiated by incorporating polymethyl methacrylate (polymer) with methyl methacrylate (methyl methacrylate) (monomer). (2)

Heat is used to complete the polymerization of this form of PMMA resin. When employed in dental prosthesis, this resin exhibits linear deformities due to contraction, with a theoretical shrinkage of 6%. Internal stresses are induced during polymerization when the traditional technique is used. When the prosthesis is withdrawn from the gypsum mould and flask, these stresses are released, resulting in twisting, bending, and dimensional changes of the denture bases when compared to the cast. Clinically, these deformations cause a loss of precision and total denture retention.

In recent years, the use of computer-aided design and computer-aided manufacturing (CAD-CAM) systems to fabricate complete dentures has increased in popularity in both clinical and laboratory contexts. This growing importance can be attributed to advancements in CAD-CAM technology, as well as more flexibility in combining aspects of the digital workflow with traditional clinical and laboratory protocols, as well as increased awareness among dental practitioners and laboratory workers. To create CAD-CAM complete dentures, two CAD-CAM processes are available: a computerised numeric control subtractive milling process and a rapid prototyping (RP) system, also known as 3D printing, an additive manufacturing process. Milling process wastes large quantities of denture base material, and more recent 3D prototyping promises a more sustainable additive approach by using less denture resin. (3,4)

In the manufacturing industry, as well as in areas such as medical care, research and education, additive manufacturing using 3D printers has become a focus of attention. In the field of prosthetic dentistry, the ability of additive manufacturing to mold multiple materials in combination based on CAD data influences the overall quality, the mechanical properties of printed parts, the total cost and the manufacturing time. (5)

The alveolar arch shape divided into variables of measurement and condition. According to some researchers, there are some classifications of alveolar arch shape, which clinically consist of a square shape, tapering form, an ovoid shape. Arch shape is an essential parameter for analyzing and valuing tissue bearing in the edentulous jaw related for better denture retention and stabilization and for the pre-prosthetic treatment plan. (6)

The shape of the jaw arch, according to Kawabe (1992), has three types: {1} Tapering, it has a narrow anterior and becomes wider toward the posterior; {2} Ovoid, it has a round part, either in the anterior or in the rear; {3} Square, it has right and left sides, which almost run parallel. (7)

In prosthodontics, arch form is extremely important in the development of any artificial dental prosthesis. It provides crucial information on tooth selection and arrangement.. (8)

For numerous years, denture bases are flexed repeatedly during chewing. This can frequently result in the prosthesis mechanical deformation and failure due to fatigue. The minimization of unanticipated denture distortion, which is as crucial as constructing dentures accurately, is a key element for the longevity of dentures and maintaining good oral health.

The majority of past studies attempted to assess denture deformation and accuracy in two dimensions. Nowadays some authors have attempted to examine dimensional stability, utilizing a surface matching program and a scanning device; it is possible to compare two things three-dimensionally. [9,10]

The concept that the mechanical loading force delivered in the laboratory is similar to the forces experienced during chewing would improve the test results' reliability.

Null hypothesis

The first null hypothesis was that no differences in mandibular denture base deformation for conventional heat-cured and 3d printed dentures following thermo-mechanical stresses application. The second null hypothesis was that there would be no difference in mandibular denture base deformation with different arch forms (square, ovoid, tapered) .

The purpose of this in vitro study was to analyze and compare the effect of thermo-mechanical stresses on mandibular denture base deformation for conventional and 3d printed mandibular denture bases.

METHODOLOGY

Sample size calculation

Sample size calculation was based on mean difference of deformation patterns between different materials retrived from previous research. [12] Using G power program version 3.1.9.4 to calculate sample size based on effect size=2.14, using 2-tailed test , α error =0.05 and power = 80.0%, the total calculated sample size will be 5 in each group.

Formation of completely edentulous mandibular casts with different arch forms

Three standard ready-made edentulous mandibular model casts with square, ovoid and tapering arch forms, free from undercuts were attributed to this study (used as the references models for the groups) (fig. 1A). Custom-made silicon molds of the edentulous mandibular models are used to fabricate epoxy resin models for the three edentulous arch forms (fig. 1B). Fifteen stone casts were obtained by pouring hard dental stone type III (Snow Rock, Korea) into custom-made silicon molds. So that five casts (n = 5) were attributed to each group (5 each of square, ovoid, and tapered arch form). Indexing of the base of each stone cast was performed to enable denture remounting on the articulator.

Fig. (1) A, completely edentulous mandibular jaw models with square, tapered, ovoid arch forms. B, epoxy resin casts of the reference models

The approach employed by Kawabe was utilised to examine and measure various arch forms. [12, 13]

1. An arch that is square : The gap between canines is broader, and the posterior ridge is more parallel than the other varieties, and the anterior ridge curvature is slight.
2. Ovoid arch form: When the distance between the canines is narrower and the anterior ridge curvature is greater than in a square arch.
3. Tapering arch form: Canines are closer together and the anterior arch curvature is more extreme than other arches.

Grouping of the Study

According to the technique of complete denture construction, samples were divided into two main groups: (15 samples for each group)

GI: Mandibular dentures constructed by additive manufacturing technique, forming a three -dimensional printed resin dentures.

GII: Mandibular dentures constructed using water bath curing method (long cycle), forming conventional mandibular resin dentures

And according to the mandibular arch form, each group was sub-divided into three equal sub groups (five samples for each arch form) as follow:

GI square/ GI ovoid/ GI tapered: Mandibular complete dentures constructed by additive manufacturing technique, with Square, ovoid, tapered arch forms .

GII square/ GII ovoid/ GII tapered: Mandibular complete dentures constructed using conventional heat-cured PMMA with Square, ovoid, tapered arch forms.

Conventional complete denture construction

For each arch form group, on a semi-adjustable articulator (Quick Master, France), the reference mandibular cast was mounted with its occlusion block. Five identical sets of appropriate sizes of mandibular denture teeth were chosen, and one set of them was used to set up teeth for the mounted master occlusion block. After that, the waxing up of the trial denture was finalized to create a master mandibular waxed-up denture that represented the reference model

Duplication of the reference waxed-up denture was performed via a pourable silicone duplicating material (Dupliflex silicones, Protechno, Spain) in a custom plastic flask to create the same denture base contours and teeth positions.

A custom plastic flask was used for the duplication process. The reference mandibular waxed-up denture with its master cast was housed on the base of a custom flask, so that at least 5 mm clearance was available all around. Duplicating material was poured under vibration; once it set, the cast with the waxed-up simulated denture were removed. This created fixed silicon mold,in which five identical waxed-up mandibular dentures were produced.

In the silicon mold, an identical set of mandibular denture teeth has been implanted in their respective positions. The cast was secured in its position in the silicon mold, and the molten wax filled the area between the teeth and the cast. Once the wax was dried, the cast with the formed trial denture were carefully removed from the silicon mold. These protocols were repeated until all similar, 5 waxed up trial mandibular dentures were created for each arch form group

For further verification, that all teeth with simulated waxed dentures were located in the same spatial position and vertical dimension that the mandibualr reference waxed-up denture was employed on the articulator; a plaster jig was built on the upper member of the articulator opposing the mandibular reference waxed-up denture. All the mandibular waxed-up dentures were mounted against this jig, and the occlusal surface of the teeth was oriented against the stone matrix until the incisal pin reached the incisal table. [14]

On the duplicated mandibular casts (squared, ovoid tapered arch forms). Processing and curing procedure was performed by conventional compression method. After waxes were washed out with boiling water, heat polymerized acrylic resin (Lucitone 199, Dentsply International Inc, York, NY, USA) was packed into the mold and polymerized for 9 hours at 72°C and maintained for 30 minutes at 100°C. The curing flasks were bench cooled to room temperature after polymerization, and the denture base samples were removed from the working cast.

The denture bases were polished with a wet rag wheel and pumice, ultrasonically cleaned for 10 minutes in alcohol, and stored for 14 days in distilled water at 37°C. (fig.2)

Fig. (2) Conventional complete denture construction.

Three-dimensional dentures printing (3d printed) complete mandibular denture construction

The reference master casts of each group(square ,tapered and ovoid) were digitized using a lab scanner (Swing, DOF lab, Korea) followed by another scanning of the reference casts with waxed up denture after spraying opacifier on the waxed-up denture to be detected by the scanner (fig.3-A, B). The 3D-scanned data from both digital scanning was saved in a standard tessellation language file (STL).

The planned virtual denture was designed by subtracting the scanned cast from the scanned cast with waxed-up denture using blender software (Blender, Netherlands) with the aid of Boolean subtract function (fig.3-C). This virtual denture was considered as a reference and saved separately in an STL file, which was then sent to slicer software (Chitubox, China).

From this reference, CAD mandibular denture, 5 mandibular digital light processed (DLP) denture for each arch form group were fabricated. 3D-printable Resin liquid (Dental Sand A2, Harzlabs, Russia) was added to the 3D printer (Photon, Anycubic, China). Printing was started with a build angle of 450, and printing thickness on the z-axis was set at 50 microns. Supports were selected without interrupting the fitting surface of the denture. (fig.3-c, d) After printing, the supports were removed, and the printed dentures were cleaned in an ultrasonic bath with ethyl alcohol for 10 minutes to remove excess resin.

The denture bases were post-polymerized for 40 minutes using an ultraviolet polymerization unit (bre.Lux power Unit 2, Bredent, Germany) as instructed by the manufacturer.

The internal surface of each fabricated heat-cured and 3D-printed denture was scanned separately prior to the process of thermo-mechanical cycling and was saved as an STL file. To ensure that each denture base specimen was mounted in the same position on the scan table, a silicone putty index was made for each denture base specimen and attached to each denture base. [15]

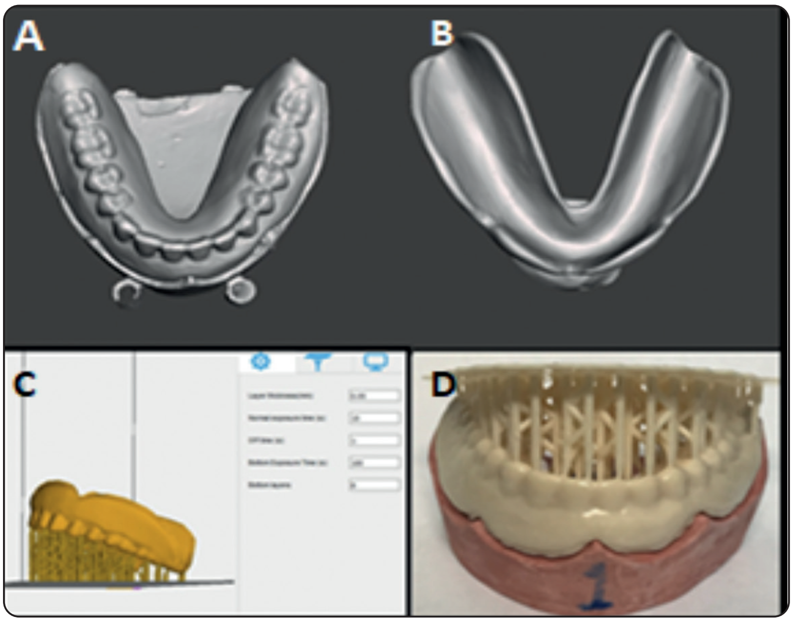

Fig. 3 A,B digitized waxed-up denture, C) planned virtual denture by subtracting, D) 3D-printed denture

Thermo-mechanical cycling of mandibular complete denture

Thermo cycling procedures for laboratory testing.

Laboratory simulations of clinical service are often performed because clinical trials are costly and time consuming. Thermal cycling is an in vivo process often represented in these simulations, but the regimens used vary considerably and, with few exceptions, are always proposed without reference to in vivo observations. Standardization of conditions is necessary to allow comparison of reports.

The mean low-temperature point for earlier in vitro studies was 6.6°C (range 0–36°C, median 5.0°C). The mean maximum temperature was 55.5°C (range 40–100°C, median 55°C). Only hot and cold temperature points were employed in the majority of the reported studies. The number of cycles used ranged from one to one million, with a mean of around 10,000 and a median of 500 cycles. [16]

In this study the number of cycles used was 500 cycle according to ISO specification. Dwell times were 25 s. in each water bath* with a lag time 10 s. The low-temperature point was 5˚C). The high temperature point was 55˚C. (fig.4 A). [17]

Mechanical-cycling procedures for laboratory testing.

Mechanical aging test was conducted using the newly developed four stations multi-modal ***ROBOTA*** chewing simulator* integrated with thermo-cyclic protocol operated on servo-motor (Model ACH-09075DC-T, AD-Tech Technology CO., LTD., Germany)

ROBOTA chewing simulator which has four chambers simulating the vertical and horizontal movements simultaneously in the thermodynamic condition. Each chamber has an upper hardened steel stylus holder that can be tightened with a screw for use as opposing materials, as well as a lower plastic sample holder in which the specimen

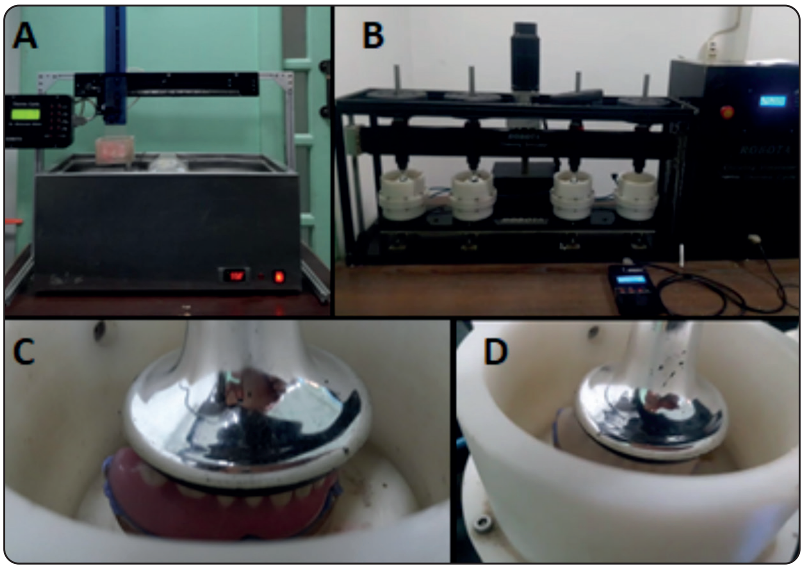

Fig. 4 A, Thermo- cycling procedures, B Four stations multi-modal ROBOTA chewing simulator, C,D mechanical-cycling of conventional and 3D printed dentures

can be inserted. A weight of 5 kg was used, which corresponded to a chewing force of 49 N. The chewing condition was tested 10,000 times. (fig.4 B,C,D). [18]

Following thermo-mechanical cycling, All completed denture bases were hydrated and their inner surface was scanned using dental lab scanner

Assessment of denture base deformation due to thermo-mechanical cycling

Denture base deformation was verified by superimposing the output of each STL file of the scanned mandibular dentures following thermo-mechanicalcycling on that prior to the thermo-mechanicalcycling procedure using best fit algorithm of 3D data inspection software (GOM Inspect, GOM) in order to compare and to calculate the deformation.

The color coded 3D-surface deviation spectra were set to have a maximum critical value of ±0.8 mm and visually displayed the At each measurement site, the discrepancy between the two superimposed data were measured in mm, tabulated and statistically analyzed. (fig 5)

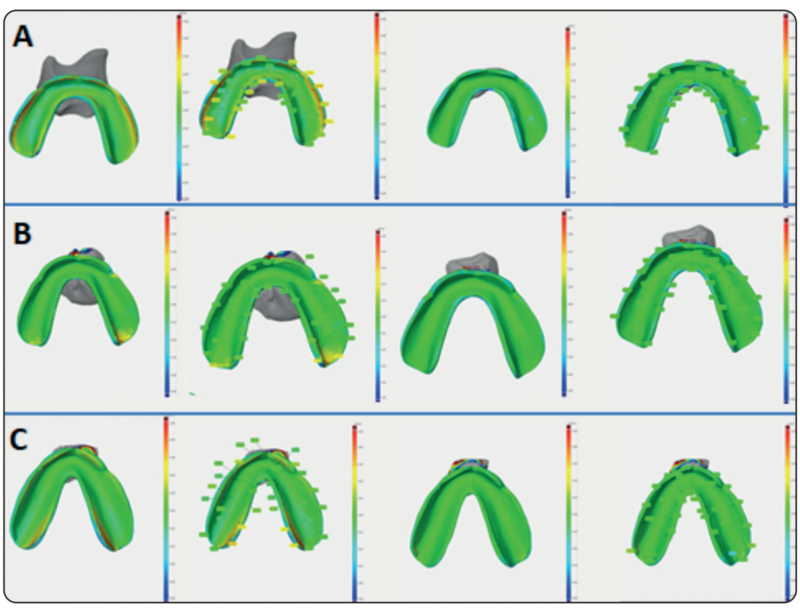

Fig. 5 (A,B,C): Assessment of denture base deformation for square,ovoid and tapered arch form respectively

RESULTS

Data were fed to the computer and analyzed using IBM SPSS Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp. Deformation was described using d mean, standard deviation after testing normality using Shapiro-Wilk test. Significance of the obtained results was judged at the (0.05) level. Student t-test was used to compare 2 independent groups, One Way ANOVA test was used to compare more than 2 independent groups and Two Way ANOVA test was used to compare effect of combined independent factors on single continuous parametric outcome.

Table (1): showed that for 3d printed mandibular denture bases, there was statistically significant higher mean deformation in favor to the square arch form (0.167±0.09) than tapered and ovoid. For conventional heat-cured mandibular denture bases; there was statistically lower mean deformation among tapered followed by ovoid, with highest denture base deformation was detected for square arch form (0.0346±0.005) without statistically significant difference between square and ovoid.

Table (2): showed that combined effect of deformation in (square /ovoid /tapered) and (3D Printed /conventional) illustrated statistically significant effect on deformation of complete denture in favor to the 3d printed group with 63.1% of deformation is detected by this combination(R Squared = .631).

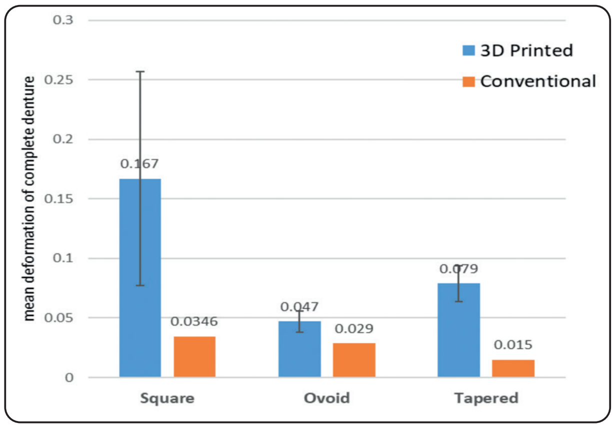

Fig. (6): mean deformation' values for CDs.

TABLE (1): Comparison of complete denture deformation among studied groups.

		Square	Ovoid	Tapered	Test of significance (One Way ANOVA test
Deformation of mandibular complete denture	***GI*** 3d Printed	0.167±0.09	0.047±0.009^{A}	0.079±0.015^{A}	F=6.79 P=0.01*
	GII Conventional heat-cured	0.0346±0.005^{B}	0.029±0.003^{B}	0.015±0.004	F=24.78 P<0.001*
Test of significance (Student t test)		t=3.26 p=0.01*	t=3.99 p=0.004*	t=8.69 p<0.001*	

Similar superscripted letters denote non- significant difference between groups by Post Hoc Tukey test

TABLE (2): Two-Way ANOVA test to study combined effect of thermo-mechanical stresses on deformation of complete denture

Source	Type III Sum of Squares	df	Mean Square	F	P
Corrected Model	.078[a]	5	.016	10.903	.001*
Intercept	.115	1	.115	79.965	.001*
Tapered /ovoid /square	.023	2	.012	8.092	.002*
3D Printed /conventional	.038	1	.038	26.826	.001*
Combined effect	.017	2	.008	5.754	.009*
a. R Squared = .694 (Adjusted R Squared = .631)					

DISCUSSION

The intimate contact between the denture base and its basal tissue ensures that the denture is secure to the patient's comfort, retention, and stability. However, in order to keep the denture in place for longer and preserve good dental health, limiting unexpected denture distortion is just as vital as constructing the denture accurately. As a result, after the denture was accurately fabricated, maintaining its accuracy would be a critical factor in ensuring the denture's lifespan.

When complete dentures are worn, they are subjected to heavy chewing stresses. This causes cyclic deformation of the denture polymer, which can lead to denture cracking and fatigue fracture. As a result, resin deformation resistance is essential. [19]

Compression moulding is still widely used in the denture manufacturing. As a result, heat-cured resin and the compression moulding method were used in this research. During the polymerization process, there has always been a problem with acrylic resin shrinkage. The linear expansion coefficient of the resin is 8.1×10. The gypsum components that make up the mould have a linear expansion coefficient of 1/8 that of acrylic resin. This discrepancy adds to the induced strain and dimensional change. During the polymerization process, PMMA resin monomer can shrink by up to 21% in volume. Water sorption might theoretically compensate for processing shrinkage by expanding the dentures. [20]

Many previous researches have been carried out to assess the amount of deformation that occurs in the denture base and the accuracy with which it is fitted. The majority of them, however, were investigated using linear or cross-sectional analysis. The majority of early investigations used an optical microscope to measure the distance between denture landmark points, while some of them used simple calipers. These methods were limited for overall deformation, contrary to our findings, because measuring the two spots was essentially a linear analysis. [21, 22]

In comparison to conventional CDs, the CDs created using a digital workflow appear to fit better with the underlying tissues. [23, 24]

There are other significant reasons to move forward with digital transformation. Traditional removable prosthodontics necessitates experts with a wide range of skills and expertise, and the outcome is technique-dependent, as errors can accumulate during the multiple manufacturing steps.. Finding qualified dental technicians to make high-quality removable dentures is difficult. Furthermore, the conventional technique is more difficult to track and record for post-hoc quality control and procedure optimization, which can be beneficial to both the patient and the dentist. [25]

Wang et al. [26] conducted a literature review to investigate the influence of the manufacturing technique on CD adaption and occlusion. All of the prostheses they studied had a clinically acceptable fit, according to their findings. The CAD/CAM CDs demonstrated a similar, if not superior, adaptability to traditional prostheses.

The quantity of residual ridge resorption varies a lot between people and even between various areas of the mouth. [6] These differences are significant in prosthetic dentistry practise.

Thermal cycling has the advantage of simulating oral conditions by exposing test materials to thermal stress that resembles the oral cavity. Aging has an unfavorable effect on the mechanical properties of denture base material, reducing its durability and long-term clinical use. [27, 28]

Hence, in this study, all materials were exposed to thermocycling (500×5°C/55°C) in a water bath before testing. According to ISO standard (ISO 11405), this study reported temperatures of 5˚C and 55˚C to test dental materials, considering these values as the closest to the physiology of the oral cavity. [11]

The present study revealed denture base deformation in all of the tested groups. This could be because the hot water accelerated the uptake of water during thermocycling, resulting in plasticization of the polymer and decreased mechanical properties, giving rise in denture base deformation when mechanical stress was applied. [29] This was in accordance with the study showed a decrease in the flexural strength of the tested 3d printed and heat denture base resin samples after thermal cycling. [30]

Thermocycling is caused by two factors: first, water sorption, which works as a plasticizer, breaking the polymer chain. The second factor was the temperature, which increased water intake and hence doubled the water sorption effect. Because this is a temperature-dependent process, the resin's mechanical characteristics deteriorate. [28, 31]

However it was found that a greater discrepancy in denture base deformation existed between the 3d printed and conventional denture base group following thermo-mechanical stresses application which was in favor to 3d printed group. This may be due to the decreased mechanical properties (particularly the flexural strength) of 3d printed denture base material rather than the conventional heat-cured ones. The flexural strength reflects the material's stiffness and rigidity as well as the ability of the material to equally distribute the forces to the underlying structures. It was in accordance with the studies revealed that, conventional heat-polymerized denture base samples show higher flexural strength mean values than the 3D-printed samples. [32,33]

A material's flexural strength is defined as the highest bending stress that may be given to it before it yields. The 3D printed material had the lowest flexural strength, elastic modulus, fracture toughness, and work of fracture. This can be explained by the reactivity of 3D-printing resin monomers combined with the curing condition, which resulted in a lower degree of double bond conversion as relative to conventional acrylic resins. [32,34] Another cause for the lower mechanical properties could be the weak interlayer bonding between successive printed layers. [35,36]

The heat polymerized PMMA may contain a percentage of residual monomers that serve as a plasticizer and reduce the stiffness of the material when processed using a conventional moulded procedure. [19,37] While 3D printing the denture base samples with photopolymerized monomers resulted in a higher amount of residual monomers, lowering the materials' stiffness due to the "plasticizer effect." [38-41]

The elastic modulus is a key parameter for determining the rigidity of a material. Elastic deformation will be more resistant to resins with a greater modulus of elasticity. The residual monomer content would influence the modulus of elasticity. High monomer content has been proven to lower the glass transition temperature, making the resin more flexible. [42]

The present study indicated a marked denture base deformation for the square arch form for both groups, with statistically significant higher mean deformation in in GI, without statistically significant difference between square and ovoid in GII .this might be due to the fact that the square arch form introduced a marked resistance to rotational forces with inability to dissipate the forces applied with the thermo-mechanical cycling, together with to the decreased mechanical properties of the 3d printed denture bases. [43] This was in accordance with the House's classification stated that, there are three arch shapes: [1] Class 1: Square; the square arch shape is the best shape for prevention from rotational movement; [2] Class II: Tapering; tapering form offers resistance to move but with a smaller degree than that of square shape; and [3] Class III: Ovoid; ovoid shape, since it becomes round, gives a little or no resistance to rotational movement. [44]

Moreover, the increased surface area of the square shape arch form may play a role in the marked increase in deformation for the square arch form for both the 3d printed and conventional heat -cured denture base groups The increased surface area introduced a wider area available for the dimensional changes and deformation of the denture bases. [13]

CONCLUSIONS

Within the limitations of this study, it can be concluded that, the first and the second null hypothesis were rejected. Increased deformation was found for the 3d printed mandibular denture bases rather than the conventional heat-cured group. Moreover square arch form mandibular denture bases introduced higher deformation values for different arch forms in both groups.

Conflict of interest

The current study exhibited author self-funding, without any conflict of interest.

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