Original Article

An in vitro comparison of the dimensional stability of four 3D-printed models under various storage conditions

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ABSTRACT

Objectives: To investigate the dimensional stability of various 3D-printed models derived from resin and plant-based, biodegradable plastics (PLA) under specific storage conditions for a period of up to 21 weeks.

Materials and Methods: Four different printing materials, including Draft V2, study model 2, and Ortho model OD01 resins as well as PLA mineral, were evaluated over a 21-week period. Eighty 3D-printed models were divided equally into two groups, with one group stored in darkness and the other exposed to daylight. All models were stored at a constant room temperature (20°C). Measurements were taken at 7-week intervals using the Inspect 3D module in OnyxCeph software (Image Instruments GmbH, Chemnitz, Germany).

Results: Dimensional change was noted for all of the models with shrinkage of up to 0.26 mm over the study period. Most contraction occured from baseline to T1, although significant further contraction also arose from T1 to T2 ($P < .001$) and T1 to T3 ($P < .001$). More shrinkage was observed when exposed to daylight overall and for each resin type ($P < .01$). The least shrinkage was noted with Ortho model OD01 resin (0.16 mm, SD = 0.06), and the highest level of shrinkage was observed for Draft V2 resin (0.23 mm, SD = 0.06; $P < .001$).

Conclusions: Shrinkage of 3D-printed models is pervasive, arising regardless of the material used (PLA or resin) and being independent of the brand or storage conditions. Consequently, immediate utilization of 3D printing for orthodontic appliance purposes may be preferable, with prolonged storage risking the manufacture of inaccurate orthodontic retainers and appliances. (*Angle Orthod*. 2024;94:346–352.)

KEY WORDS: 3D printing; Resin; Orthodontic; Shrinkage; Dimensional stability

INTRODUCTION

In recent years, additive manufacture (AM) involving 3D printing has become increasingly popular in orthodontics, with conventional plaster models being gradually phased out as a result.[1,2] Printed models have been used extensively in orthodontics, including in the fabrication of retainers, aligners, indirect bonding trays, and functional appliances. An appreciation of the dimensional stability of these models under different storage conditions is important, with shrinkage potentially precluding their reuse for appliance fabrication.

AM has been defined as a process involving vat polymerization, material extrusion and jetting, binder jetting, powder bed fusion, sheet lamination, and directed energy deposition.[3] Among these, vat polymerization has emerged as one of the most well-established methods. Stereolithography (SLA), liquid crystal display (LCD), and digital light processing (DLP) represent commonly used photopolymerization-based 3D printing systems. The use of vat polymerization has access to economical portable 3D printers. Notwithstanding this, vat polymerization necessitates an involved process requiring postproduction processing, including removal of unpolymerized resin and support structures and the need for additional polymerization.[4,5] These processes

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are fallible, with the potential for inaccuracy with associated implications for subsequent appliance manufacture. Another AM method is fused filament fabrication (FFF), which involves the layer-by-layer extrusion of thermoplastic filament and is known for its cost-effectiveness. This 3D-printing method needs no postprocessing.

Previous research has exposed the propensity for shrinkage of 3D-printed models with commercially available resins associated with contraction of 9.19% to 11.2% over a 39-day period and a novel resin displaying less volumetric shrinkage (7.28%), high accuracy, and suitable mechanical properties.[6] Similarly, differences in the dimensional stability of printed models were observed based on mode of production, with DLP being less accurate than material jet production.[5] In addition, storage under light is thought to lead to further compromise in dimensional stability.[5,7]

Various studies have investigated different 3D printing methods for the production of dental models. DLP printers have a significantly higher level of precision compared with LCD, SLA, and FFF printers.[8,9] But the manufacturing parameters, including layer thickness, base design, postprocessing, and storage, may significantly influence the accuracy of the model. A fully solid design can result in enhanced precision.[10] Storage has an impact on 3D-printed models and can significantly affect accuracy for up to 6 weeks after printing.[11] In addition, the accuracy as well as the surface color is influenced by exposure to light over extended periods of storage.[12]

Gypsum-based stone models are known to undergo contraction during the early setting stages, followed by isotropic expansion. Maximum acceptable thresholds for the linear expansion of dental gypsum have been set at 0.15% to 0.3%.[13] There is, however, a paucity of information concerning the dimensional accuracy of 3D-printed dental models, with limited appreciation of the impact of resin type and storage conditions. This knowledge is important for the fit integrity of active orthodontic appliances and retainers, influencing their fit, acceptability, and effectiveness.[14,15] To assess dimensional differences, the registration of 3D models can be performed using the iterative closest point (ICP) algorithm. This advanced method enables calculation of distances between the point clouds and meshes for each point of the printed model by identifying the nearest triangle on the reference mesh.[16–18]

A comprehensive analysis of dimensional and shape changes associated with 3D-printed models under various conditions is required to provide insight into the optimal handling, potential, and limitations of the use of 3D-printed models in orthodontics. Therefore, the aim of this study was to investigate the dimensional stability of a range of 3D-printed models under specific storage conditions. The null hypothesis was that printed models are dimensionally stable, with stability unaffected either by printed material or storage condition.

MATERIALS AND METHODS

A laboratory-based study was undertaken to evaluate the dimensional stability of four different printing materials over a 21-week period. Sample size was calculated based on the comparison of dimensional change using three repeated measurements, assuming shrinkage values of 0.5, 0.1, and 0.15 vs 0.1, 0.15, and 0.02; a correlation coefficient between repeated measurements of 0.5; variance error of 0.005 (standard deviation 0.07^2); and power of 90%. This resulted in a required sample of nine units per group. A base value of 10 was therefore used for each resin.

Eighty 3D-printed models were divided equally into two groups, with one group stored in darkness and the other exposed to daylight. All models were held at a constant room temperature (20°C). The four printed materials included Draft V2 resin (photopolymer resin; Formlabs Inc, Somerville, Mass), study model 2 white resin (photopolymer resin; SprintRay Europe GmbH, Weiterstadt, Germany), Ortho model OD01 resin (photopolymer resin; Shining 3D Technology GmbH, Hangzhou, China), and PLA mineral (polylactic acid; Fiberlogy, Brzezie, Poland). Measurements were taken at baseline (T0), 7 (T1), 14 (T2), and 21 (T3) weeks.

All resin models were aligned vertically for printing, whereas the filament models were aligned horizontally. The models were printed with a fully solid design on the following printers: Ortho model OD01 on the Shining 3D Accufab-L4D (Shining 3D Technology GmbH), Draft V2 on the Formlabs Form 3 (Formlabs Inc), study model 2 on SprintRay Pro95 S (SprintRay Europe GmbH), and the PLA mineral filament on the Artillery Genius Pro (3djake GmbH, Paldau, Austria). All printers use different printing methods: Accufab-L4D involving LCD, SprintRay Pro95 S using DLP, Formlabs Form 3 using SLA, and Artillery Genius Pro based on FFF. After printing, the resin models were washed in the Formlabs Form Wash using isopropanol for 10 minutes. Then, the resin models were cured in the Formlabs Form Cure for 5 minutes. The filament models required no postprocessing.

The Inspect 3D module in OnyxCeph software (Image Instruments GmbH, Chemnitz, Germany) was used to record model dimensions. This module offers a range of functions for measuring distances and areas on 3D data sets, allowing measurements to be performed on individual objects and in relation to individually aligned reference structures. The printed models were scanned at 7-weekly intervals over a period of 21 weeks using the Launca DL-206 scanner (Launca Medical Device Technology Co Ltd, Guangdong, China) to obtain STL models. These were

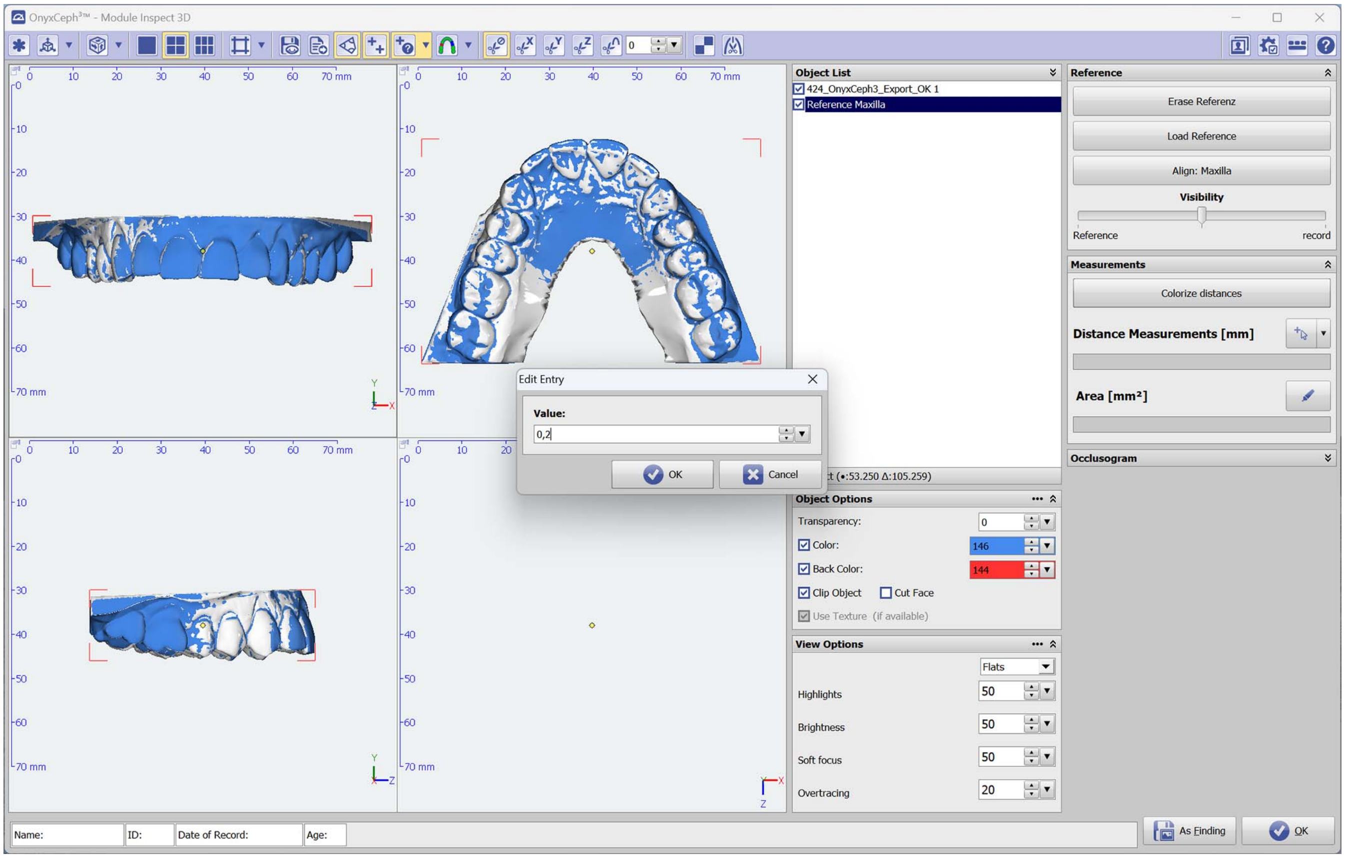

Figure 1. The use of color change (with a threshold value of 0.2 mm) to demarcate dimensional differences using the Inspect 3D module.

imported into OnyxCeph software (Image Instruments GmbH) and opened in the Inspect 3D module. All scanned models and the reference model were selected and aligned precisely with the maxillary teeth (17–27) marked as the specific area of interest. The Inspect 3D module uses model registration performed through the ICP algorithm. Threshold values for color changes were set to 0.2 mm, to demarcate visible dimensional differences (Figure 1).

The color changes permitted the identification of the highest deviations, facilitating an understanding of shape changes. The analysis was conducted using the Distance Reference as the chosen measurement method. The measurement results were visually captured and recorded for further analysis and evaluation (Figure 2).

Statistical Analysis

Descriptive statistics were calculated and plotted based on printed material (Draft V2 resin, study model 2 resin, Ortho model OD01 resin, or PLA mineral), light exposure, and time interval (T1–T3). To evaluate the shrinkage pattern, a population average generalized estimating equation model, including type of printed material, light exposure, time and resin time interaction, and robust standard errors was fitted. Wald tests were used to test the significance of the main and interaction effects for the included predictors. All analyses were conducted in Stata 17 (StataCorp, College Station, Tex).

RESULTS

Shrinkage of all models was observed over time. While the majority of this took place over the initial 7-week period (T0–T1), further changes arose until T3 (Table 1, Figure 3).

The least shrinkage, both from T0 to T1 (0.08 mm) and over the 21-week study period (0.16 mm), occurred with Ortho model OD01 resin. Conversely, the highest level of shrinkage was noted with Draft V2 resin (0.23 mm). In addition, storage in light resulted in a higher level of contraction for three of the four materials, with the Ortho model OD01 resin being the exception (0.16 mm under both light and dark conditions).

Based on the generalized estimating equation model (Tables 2 and 3, Figure 4), all of the parameters assessed—light, resin and time, and the resin-time interaction—had statistically significant effects on material performance, with all printed models shrinking to some degree over time, irrespective of the light conditions. Overall, the Ortho model OD01 resin shrunk the least, and Draft V2 resin underwent the most shrinkage

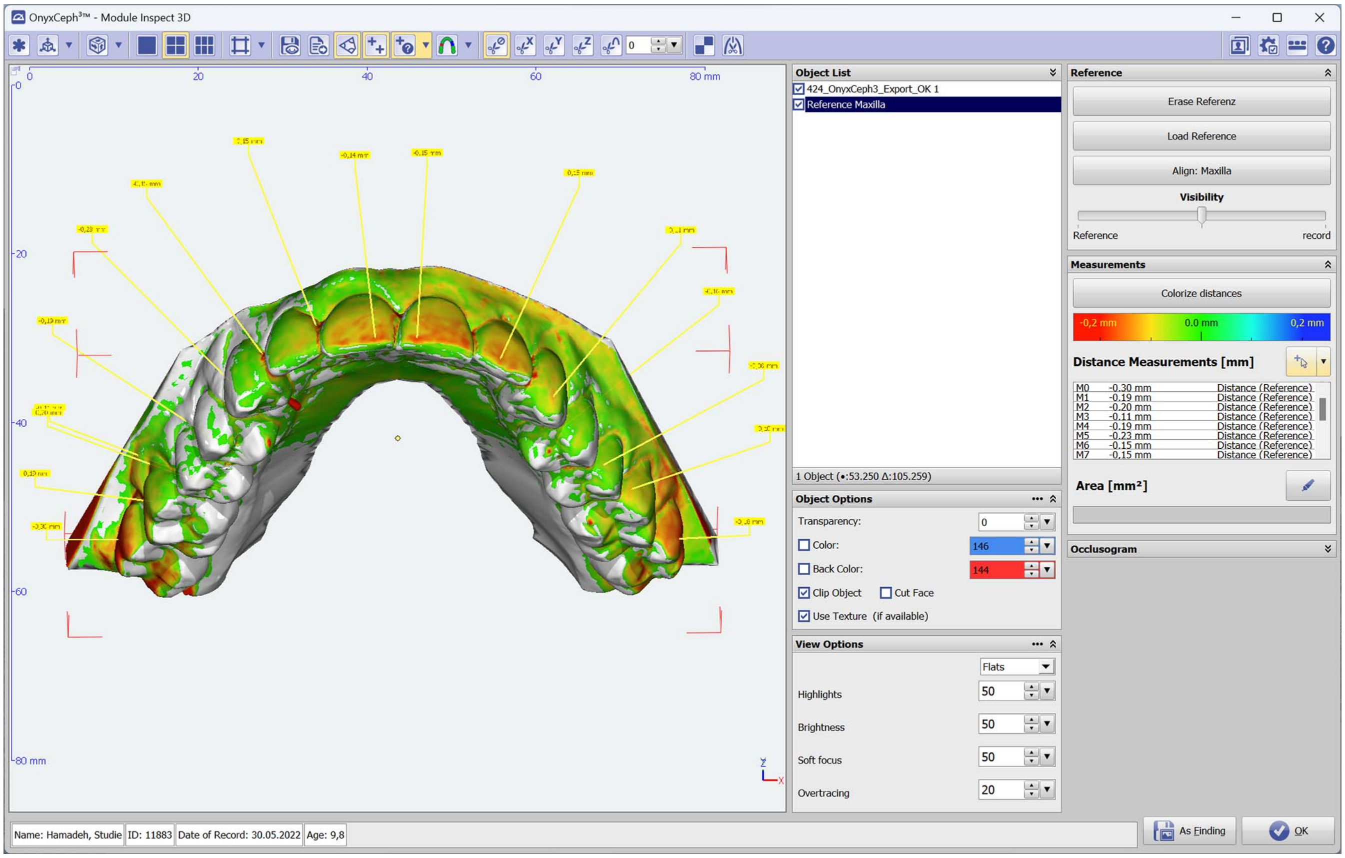

Figure 2. Color changes demarcated deviations which were recorded using the distance measurement function within Inspect 3D.

($P < .001$). Resins exposed to daylight contracted more compared with those stored in dark conditions ($P < .01$). While most shrinkage occured from baseline to T1, significant further contraction also arose from T1 to T2 ($P < .001$) and T1 to T3 ($P < .001$).

DISCUSSION

The overall findings confirmed that contraction of printed models occurs and was affected both by resin type and light conditions. In addition, while most dimensional change occurred early (within 7 weeks), further changes did appear to arise over time. These findings were consistent with data in allied dental literature with previous studies alluding to appreciable levels of constriction based on printer type, time, and storage conditions, both with resin-based and metal printing within the prosthodontic literature.[5,19–21]

The magnitude of change observed over the study period was generally small with maximal mean changes

Table 1. Mean and Standard Deviation of Shrinkage per Type of Light, Resin, and Time Point

		Time		
		1	2	3
Light conditions				
Dark				
Printed material				
PLA mineral	Mean (SD)	−0.15 (0.07)	−0.19 (0.09)	−0.21 (0.09)
Ortho model OD01	Mean	−0.08 (0.06)	−0.12 (0.06)	−0.16 (0.06)
Draft V2	Mean	−0.19 (0.07)	−0.21 (0.07)	−0.23 (0.06)
Study model 2	Mean	−0.13 (0.07)	−0.17 (0.07)	−0.20 (0.08)
Daylight				
Printed Material				
PLA mineral	Mean	−0.15 (0.07)	−0.19 (0.06)	−0.22 (0.06)
Ortho model OD01	Mean	−0.07 (0.05)	−0.12 (0.06)	−0.16 (0.06)
Draft V2	Mean	−0.20 (0.08)	−0.23 (0.07)	−0.25 (0.07)
Study model 2	Mean	−0.18 (0.06)	−0.21 (0.07)	−0.24 (0.07)

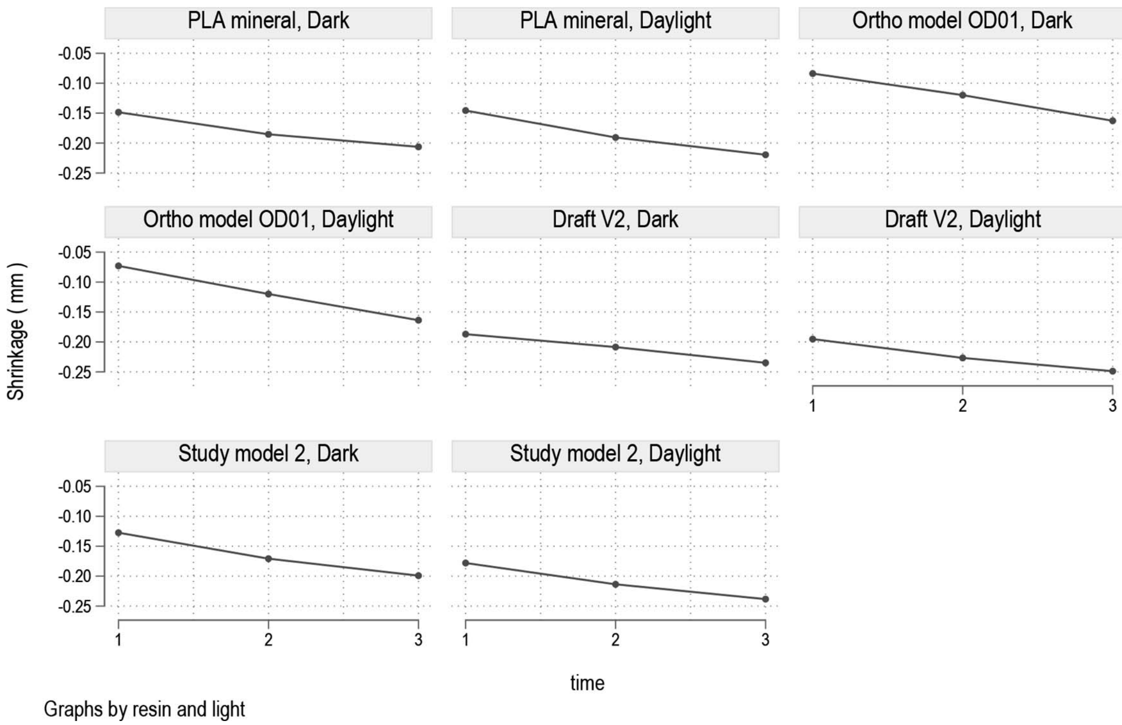

Figure 3. Graphical representation of the mean shrinkage with specific materials based on light conditions over the study period.

of 250 μm (or 0.25 mm). Notwithstanding this, this level of discrepancy may be of clinical significance with the potential to introduce unwanted tooth movement,[15] inducing local discomfort, risking root resorption, and impairing the fit of orthodontic appliances and retainers. Previous studies have alluded to constriction with PolyJet- and DLP-printed dental casts of the order of 46 and 43 μm, respectively, for simulated dental dies.[20] In a further study involving implant analogs, changes of up to 64 μm were reported with PolyJet printers.[22] The magnitude of change noted in the present study exceeded these reports, reflecting the use of complete maxillary arch models allied with the more prolonged period of evaluation of up to 21 weeks.

An allied study involving the use of complete maxillary arch models reported constriction of up to 163 μm with DLP when exposed to light and 146 μm stored in dark conditions over a 3-month period.[5] As such, the effect of light exposure was consistent among the studies, with storage in the dark being preferable and having an ongoing effect up to the 21-week point. The dimensional stability of 3D-printed models appears to be contingent on a range of factors, including the mode of production, polymerization mechanisms, choice of printed material, storage duration, and storage conditions including exposure to light.[5,23,24] Further research is therefore required to better define the optimal approach in terms of material choice, printing mechanism, and storage conditions. In

Table 2. Coefficients, 95% Confidence Intervals, and *P* Values for the Effect of Light, Resin, Time, and Resin × Time Interaction on Shrinkage

Shrinkage	Coefficient (95% Confidence Interval)	*P* Value
Resin		
PLA mineral	Reference	
Ortho model OD01	.07 (.06, .08)	<.001
Draft V2	−.04 (−0.7, −0.02)	<.01
Study model 2	−.01 (−.02, .01)	.50
Time		
1	Reference	
2	−.04 (−.05, −.03)	<.001
3	−.07 (−.08, −.05)	<.001
Resin × time		
Ortho model OD01#2	−.0006 (−.01, .01)	.93
Ortho model OD01#3	−.019 (−.03, −.007)	<.01
Draft V2#2	.014 (.002, .03)	.02
Draft V2#3	.015 (.002, .03)	.02
Study model 2#2	.001 (−.01, .01)	.81
Study model 2#3	−.0002 (−.02, .02)	.98
Light		
Dark	Reference	
Daylight	−.015 (−.03, −.004)	<.01

Table 3. Wald Test for the Overall Effect of Light, Resin, Time, and Resin × Time Interaction on Shrinkage

Parameter	χ^2	*P* Value
Resin	764.97	<.001
Light	6.80	<.01
Time	181.32	<.001
Resin × time interaction	6444.46	<.001

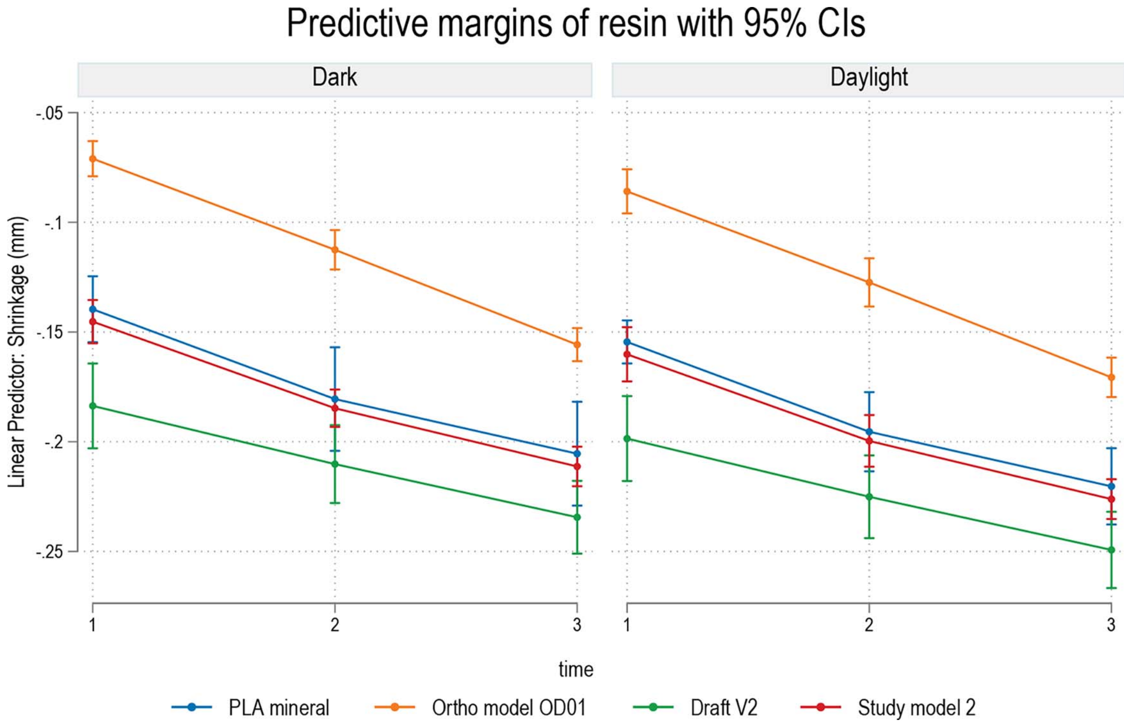

Figure 4. Predicted shrinkage based on printed material and the effects of light conditions over time.

addition, the longer-term implications of storage remain unclear; notwithstanding this, the present study suggests that storage periods in excess of 21 weeks are likely inappropriate for the later fabrication of orthodontic devices, particularly aligners and pressure-formed retainers, which rely on a hermetic seal.

In terms of the specifics of resin choice, the present findings allude to a slight superiority for Ortho model OD01-colored resin, with Draft V2-colored resin being most susceptible to dimensional change. It is nevertheless noteworthy that 50% of the observed change with Ortho model OD01 resin arose from T1 to T3, while a smaller percentage occurred with the alternatives over this period. The longer-term performance of this material relative to the alternatives is therefore uncertain. Based on the color maps, larger discrepancies arose at the extremities of the printed models, including the buccal aspects of the incisor and molar teeth. This observation is important from an orthodontic perspective, risking the introduction of unwanted orthodontic forces. In addition, changes were also noted in the palatal region, with particular implication for appliances or adjuncts reliant on palatal fit.

The environmental impact of orthodontic treatment and the increasing recourse to 3D printing is increasingly being considered both on a local[25] and global[26,27] level. These concerns have contributed to a drive to refine and ingrain the use of directly printed aligners and retainers,[28] obviating the need for printing of models. The limitations associated with the dimensional stability of printed models exposed in the present study lends further support to this trend, with the usage of stored printed models for appliance fabrication being potentially problematic.

The present study offered unique insight into the association between various printed materials and light exposure on the dimensional stability of printed models. However, the analysis was confined to four printed materials and two sets of conditions. The use of alternative 3D printers, chemical polymerization mechanisms, and alternative approaches to storage, including variation in temperature and humidity, may further affect the dimensional stability of printed models. Also, a finite evaluation period (up to 21 weeks) was considered. More sustained evaluation may therefore provide valuable insight with potential implications for the relative merits of material choices and storage conditions.

CONCLUSIONS

- Shrinkage of 3D-printed models is pervasive, arising regardless of the material used (PLA or resin) and being independent of the brand or storage conditions.
- The least shrinkage was noted with Ortho model OD01 resin, while the most appreciable level of change arose with Draft V2–printed resin.
- Less dimensional change occurs with storage in dark conditions.

- Immediate utilization of 3D-printed models is preferable, with prolonged storage risking the manufacture of inaccurate orthodontic retainers and appliances.

Declaration of Interest

The authors report there are no competing interests to declare.

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Availability of Data and Materials

The data sets and/or analyses used during the current study are available from the corresponding author on reasonable request.

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