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RESEARCH AND EDUCATION

Effects of printing layer thickness on mechanical properties of 3D-printed custom trays

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ABSTRACT

Statement of problem. The layer thickness serves as a straightforward and controllable parameter to alter the mechanical properties of 3D-printed custom trays. However, how the printing layer thickness affects the mechanical properties of the trays is not fully understood.

Purpose. The purpose of this in vitro study was to investigate the effects and their underlying mechanisms and to optimize the mechanical properties through modulation of the printing layer thickness.

Material and methods. Polylactic acid (PLA) specimens were 3D-printed with 5 layer thicknesses from 0.1 mm to 0.5 mm. The bond, flexural, and tensile strengths were measured by using a universal test machine. Postfracture interfaces were examined by means of scanning electron microscopy. Additionally, the printing dimensional accuracy was estimated by measuring the size deviations between the printed and virtual specimens, and the printing times were recorded.

Results. With increasing PLA printing layer thickness, the tensile bond strength first increased and then decreased, peaking at a thickness of 0.4 mm. While the flexural and tensile strengths decreased, the printing dimensional accuracy remained constant from 0.1 mm to 0.4 mm and then decreased at 0.5 mm. The printing time sharply decreased as printing layer thickness increased.

Conclusions. Moderate layer thickness provided the best properties for 3D-printed custom trays. (J Prosthet Dent 2020;■:■-■)

Three-dimensional printing has become popular for fabricating custom trays[1-3] because of its improved accuracy,[3,4] shorter handling time,[5] and simplified procedures.[6] In addition to requirements such as adequate strength,[7] 3D-printed custom trays must allow sufficient bond strength between the trays and the impression material[8,9] and be sufficiently rigid to support the impression materials and prevent distortion when pouring the cast.[10] Additionally, the custom tray must be accurately fabricated to ensure an accurate impression,[11] and the printing process should be time-efficient.[6]

Printing layer thickness is an accessible and controllable parameter for modulating the physical properties of 3D-printed materials.[12] Wu et al[13] reported that the thickness of printing layer influenced the tensile strength, flexural strength, and impact strength of 3D-printed polyetheretherketone. Farzadi et al[14] determined that both printing layer thickness and orientation affected the compressive strength and dimensional accuracy of 3D-printed specimens. However, the effect of printing layer thickness on the mechanical properties of 3D-printed custom trays remains unknown.

In the present in vitro study, a series of polylactic acid (PLA) specimens with various printing layer thicknesses were produced to investigate the tensile bond strength,

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Clinical Implications

Mid-range printing layer thickness is optimal for 3D-printed custom trays.

flexural strength, tensile strength, printing accuracy, and printing time of 3D-printed trays in a simulated clinical situation. The desktop-class fused deposition modeling (FDM) technique has been commonly used to fabricate custom trays; FDM is a straightforward, low-cost, and easily implemented system with a wide range of printing materials.[15-18] PLA—extracted from corn and suitable for dental applications—was selected for the present study as it is both a renewable and an environmentally friendly medical-grade material.[19] The null hypothesis was that the printing layer thickness would have no effect on the tensile bond strength, flexural strength, tensile strength, printing accuracy, or printing time of 3D-printed PLA.

MATERIAL AND METHODS

A tensile bond test, a 3-point bend test, and a tensile test were conducted to investigate the mechanical properties of PLA custom trays with 5 different printing layer thicknesses (test) and conventional polymethylmethacrylate (PMMA) (Lightplast Base Plates; Dreve Dentamid GmbH) trays (control). All the PLA specimens were designed by using a reverse engineering software program (Geomagic Studio 12.0; Raindrop). The data were stored in a standard tessellation language (STL) format and then imported into a computer connected to an FDM printer (Lingtong II; SHINOTECH) with a nozzle diameter of 0.8 mm. Five levels of common layer thickness were used: 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, and 0.5 mm; these specimens were labeled T01, T02, T03, T04, and T05, respectively. The experiments were restricted to layer thicknesses below 0.5 mm as the outer profile of the tray deforms for layer thicknesses greater than 0.5 mm. A schematic of the fabrication of a 3D-printed PLA specimen is shown in Figure 1A. The sandwich structure[20] was used to simulate the separation of the 10×10×2-mm tray specimens from polyether impression materials to determine the tensile bond strength. The geometries for the 64×10×3.3-mm flexural strength specimens and the tensile strength specimens (full length: 75 mm, narrow-parallel length: 30 mm, radius: 100 mm, double-ends width: 10 mm, narrow-parallel width: 5 mm, thickness: 2 mm) were similar to the specifications in the International Standards Organization (ISO) 178: 2001 and ISO 527-1:1993 (Fig. 1B, C, D). Five specimens of each geometry were fabricated. The printing parameters used in this study are listed in Table 1. Three geometrically distinct PMMA specimens were fabricated by using commercially available light-polymerized PMMA resin. The PMMA specimens were light polymerized (PRECI NT SHUTTLE II; Yeti Dentalprodukte GmbH) for 5 minutes on each side and cleaned with ethanol. The specimen size was verified by measurement at 3 positions on each side with electronic Vernier calipers (111N-101B; Guanglu) with a measurement range of 0 to 150 mm and an accuracy of 0.01 mm. The average value of 3 measurements was used as the final values in subsequent analyses.

For the tensile bond test, 2 PLA specimens were fixed to a screw by using a cyanoacrylate adhesive (LOCTITE 406; Henkel) and attached to a linearly movable stage by means of the screws locking into a universal testing machine (3367; Instron). The polyether impression material (Impregum Penta; 3M ESPE) was mixed in an automatic device and then injected into the gap between the tray specimens. The movable stage was actuated until the gap was reduced to 2.0 ±0.05 mm. The polyether was allowed to polymerize for 6 minutes according to the manufacturer's recommendations. Any excess polyether was trimmed with a knife before an additional polymerizing time of 24 hours.

The tensile test was conducted at a crosshead speed of 5 mm/minute by using a 490-N load until bond failure occurred. The flexural strengths of the specimens were measured by using a universal test machine with a span length of 50 mm using a 490-N load cell and a crosshead speed of 2.0 mm/min until the specimen fractured or the loading force stabilized. The tensile strengths of the specimens were measured by using a universal test machine to apply force—at a speed of 1.0 mm/minute—until the specimen ruptured. The tests were conducted in the environment with a temperature of 23 ±2 °C and a relative humidity of 50 ±10%. Subsequently, the rupture surface morphologies of the tensile bond test, the 3-point bend test, and the tensile test were observed by the scanning electron microscopy (SEM) (Sigma 300; Carl Zeiss).

The 3D printing accuracy of square PLA specimens with different layer thicknesses—the same specimens as used during the tensile bond test—was assessed by determining the deviation in dimensional lengths along all 3 principal axes between the real and the virtual objects with the electronic vernier calipers. Results were obtained in triplicate for each direction from 3 separate specimens. The printing time required to fabricate the square specimen—used for the tensile bond test—was recorded for different printing layer thicknesses (Table 2).

All data were analyzed by using a statistical software program (IBM SPSS Statistics, v20.0; IBM Corp). Analysis of variance (ANOVA) and the Bonferroni post hoc test were used to compare the groups' differences (α=.05).

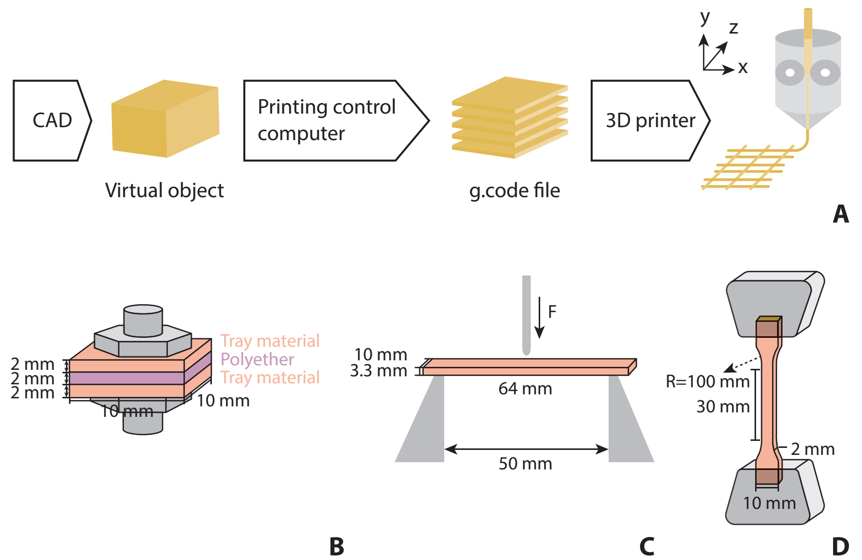

Figure 1. Study overview. A, Process flow of 3D printing technology: coordinate axes in accordance with printing orientation used. B, Tensile bond strength test. C, Three-point bend test. D, Tensile test. CAD, computer-aided design.

RESULTS

The SEM images of rupture surface morphologies after the tensile bond test are shown in Figure 2A. The ANOVA of the tensile bond test showed significant statistical differences for the 5 PLA groups and the PMMA group (P<.001) (Fig. 2B). The tensile bond strength initially increased and then decreased with increasing printing layer thickness, peaking at the T04 group. The average tensile bond strength of the 0.4-mm layer thickness group was 105%, 54.8%, 30.6%, and 56.8%, stronger than those of the T01 (P<.001), T02 (P<.001), T03 (P<.001), and T05 (P<.001) groups, respectively. No statistical difference was found between the T02 and T05 groups (P=1.000).

The SEM images of fractured surface geometries after the 3-point bend test are shown in Figure 3A. Significant statistical differences in flexural strength were found for the 6 groups (P<.001) (Fig. 3B). Groups T01, T02, and T03 withstood significantly greater flexural strain before fracture than the T04 and T05 groups (P<.001), and group T04 was better than group T05 (P=.033). The PLA groups all displayed greater flexural strength than the conventional PMMA group ($P\leq$.001). No statistical differences were found among the T01, T02, and T03 groups (P=1.000).

The SEM images of fractured surface geometries after the tensile test are shown in Figure 4A. Significant statistical differences in tensile strength were found among the 6 groups (P<.001) (Fig. 4B). The tensile strength decreased gradually with increasing printing layer thickness. Group T01 was statistically significantly higher than the T03 (P=.002), T04 (P<.001), T05 (P<.001) and PMMA groups (P<.001); group T02 was also significantly higher than the T04 (P=.007), T05 (P=.001), and PMMA groups (P<.001). Additionally, the T03 group was higher than the PMMA group (P=.002).

Table 1. Fused deposition modeling 3D printer settings

Items	Settings
Nozzle diameter	0.8 mm
Infill	100%
Layer thickness	0.1, 0.2, 0.3, 0.4, and 0.5 mm
Deposition speed	30 mm/s
Deposition direction	0 degrees with X axis
Wall thickness	0.8 mm
Nozzle temperature	210 °C

The dimensional accuracy and printing time of the tensile bond test specimens were evaluated with 5 different layer thickness groups (Table 2). No significant differences were found in length (P=.462), width (P=.596), or height (P=.298) of the specimens. The specimen volumes of the T01 (P=.027), T02 (P=.003), T03 (P=.028), and T04 (P=.005) groups were more accurate than that of the T05 group (P=.002). No significant differences were found among any other groups. When the layer thickness was increased, the printing time sharply decreased (P<.001).

DISCUSSION

This study examined the effects of printing layer thickness, an important and controllable 3D printing parameter, on the mechanical properties of custom trays. The null hypothesis was rejected for the tensile bond strength, flexural strength, tensile strength, printing

Table 2. Printing dimensional accuracy and printing time in different layer thicknesses

Layer Thickness (mm)	Length (mm), Axis X	SD (mm)	Width (mm), Axis Y	SD (mm)	Height (mm), Axis Z	SD (mm)	Volume (mm^3)	Printing Time (min)
Nominal	10	—	10	—	2	—	200	—
0.1	9.99	0.02	10.01	0.01	1.97	0.01	197.0	9.00
0.2	9.95	0.01	10.05	0.02	1.94	0.01	194.0	4.50
0.3	9.93	0.02	10.01	0.01	1.97	0.03	195.8	3.00
0.4	10.02	0.05	10.02	0.03	1.94	0.01	194.8	2.25
0.5	9.97	0.05	10.01	0.06	2.06	0.02	205.6	1.80

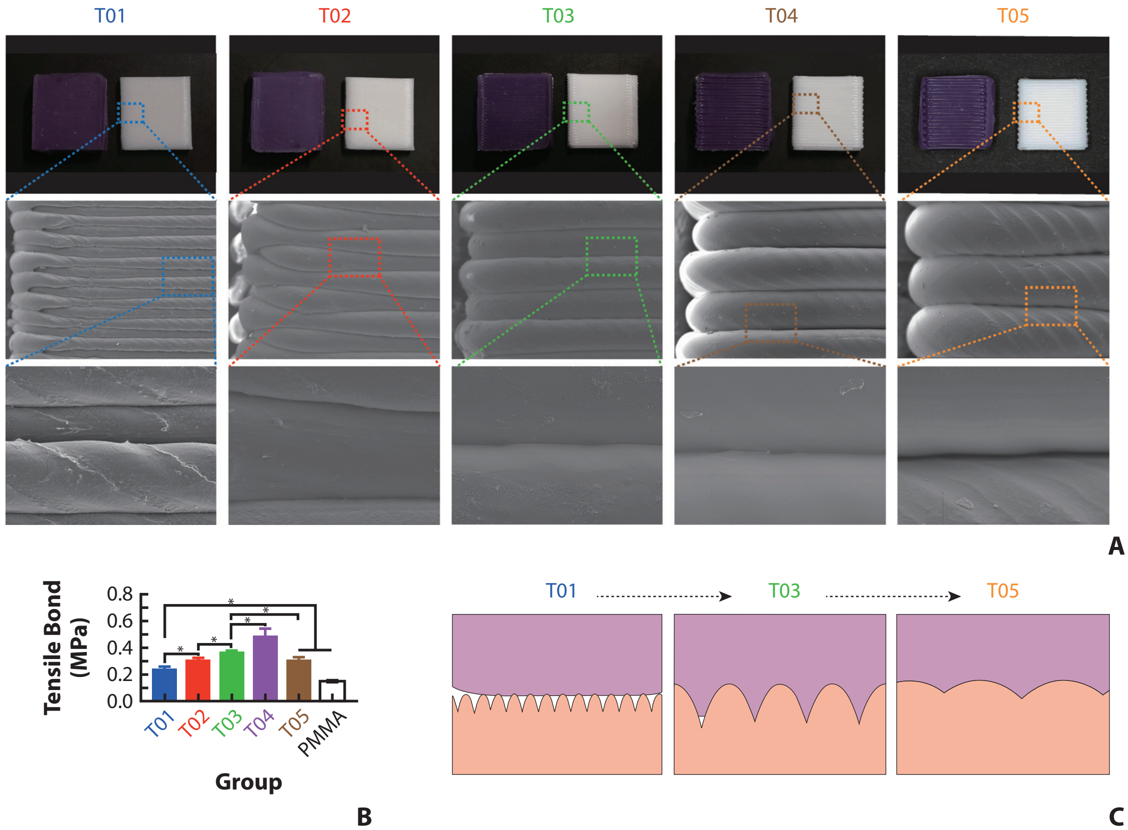

Figure 2. Results of tensile bond test. A, Digital photographs (top row) and SEM images (original magnification middle row ×100; bottom row ×500) for 5 different printing layer thicknesses. B, Tensile bond strength bar chart of 5 PLA test groups and PMMA control group. Error bar represents standard deviation, *$P<.05$. C, Explanation of mechanism: with increased layer thickness surface roughness of specimen increased. As layer thickness continually increased and approached that of nozzle diameter of printer, outer profile of each layer became more rounded, causing surface to appear flatter with surface roughness of specimen and contact area reduced. PLA, polylactic acid; PMMA, polymethylmethacrylate; SEM, scanning electron microscope.

accuracy, and printing time because when PLA printing layer thickness increased, the tensile bond strength first increased and then decreased, the flexural and tensile strengths decreased, the printing dimensional accuracy decreased at 0.5 mm, and the printing time sharply decreased. These factors and their existing mechanisms are explained from a clinical perspective.

The bond between the tray and the impression material is an important property when making impressions,[9] as debonding will lead to a distorted impression.[21] The surface roughness of the tray affects tensile bond strength.[22] The tensile bond test results suggest that the surface roughness of the specimen increased with increasing layer thickness. As the layer thickness increased and approached the nozzle diameter of the FDM printer, the outer profile of each layer became rounded, causing the surface to appear flatter. Therefore, the surface roughness of both the specimen and the contact area were reduced (Fig. 2C). Other factors, including the material performance and the surface morphology of the trays,[23] the gap between the tray and the impression material, and the process of applying the adhesive, also affect the tensile bond strength between the impression materials and the trays.[24]

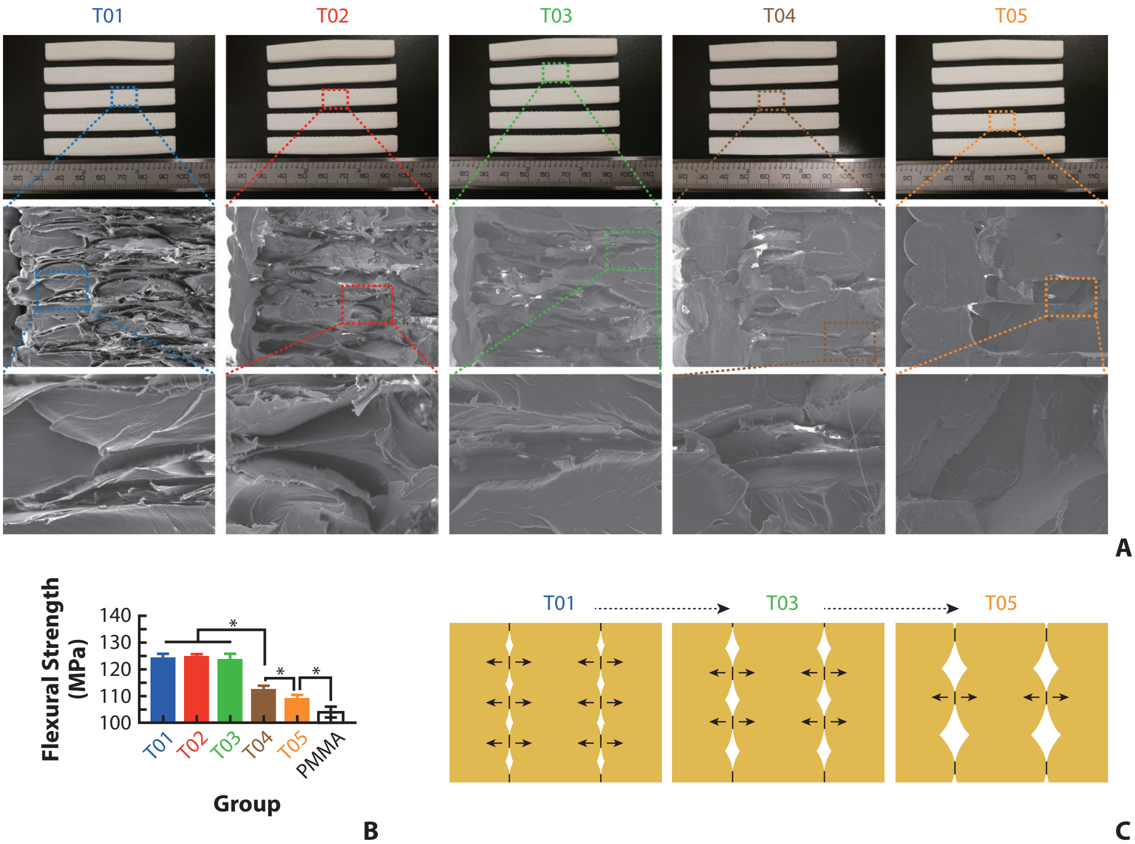

Figure 3. Fracture results of three-point bend test. A, Digital photographs (top row) and SEM images (original magnification middle row ×100; bottom row ×500) for 5 different layer thicknesses. B, Flexural strength bar chart of 5 PLA test groups and PMMA control group. Error bar represents standard deviation, $^{*}P<.05$. C, Explanation of mechanism: as layer thickness decreased, interfaces between layers became larger (*black line segment*) and internal stress being dispersion (*black arrows*), and flexural strength increased. PLA, polylactic acid; PMMA, polymethylmethacrylate; SEM, scanning electron microscope.

Differences in the flexural strengths of the 5 groups of various layer thicknesses can be seen from the SEM images and the schematic diagram (Fig. 3C). The heights of the fractured PLA filaments were inconsistent, and the fracture surface of each filament was irregular. The fracture was mainly caused by damage to the rasters during pulling, resulting in rupture. As seen in the SEM images and the schematic diagram (Fig. 4C), PLA displayed fracture and presented regular cross-sections, while the edges appeared shrunk inwardly. The nozzle of the FDM printer is circular and deposits material in a rounded form, as it is not possible to make a perfectly square nozzle.[25] Therefore, when the thickness of the printing layer was decreased, the conjoined portion between adjacent layers compactly fused; the holes present in the whole material decreased, leading to increases in both the cross-sectional area and tensile strength. Similar to the findings and conclusions from the flexural and tensile tests, the antideformation properties indicate that the performance of the 3D-printed objects is affected by the printing layer thickness.[13] Moreover, previous studies reported that the printing orientation can influence both the flexural strength and the tensile strength.[13,26] To achieve maximal nondeformability in this study, the specimens' printing orientation for both the 3-point bend test and the tensile test was fixed to be parallel to the force direction.[13]

An accurate and stable tray provides uniform thickness and sufficient space for the impression material.[2] The results of the present study suggested that a thinner layer can lead to the fabrication of more accurate custom trays. However, medium-layer thickness provided the best profiles for all the specimen groups, rather than either the thinnest or the thickest groups (Fig. 3A), which can be explained by the excessive melting of the thinnest layered specimens and the insufficient melting of the thickest layers at the application temperature of the FDM printer material (210 °C). In contrast, Kamio et al[27] analyzed the shape error by comparing the dimensions of 3D-printed objects against the dimensions set in the original designs. They suggested that adjusting the layer thickness had

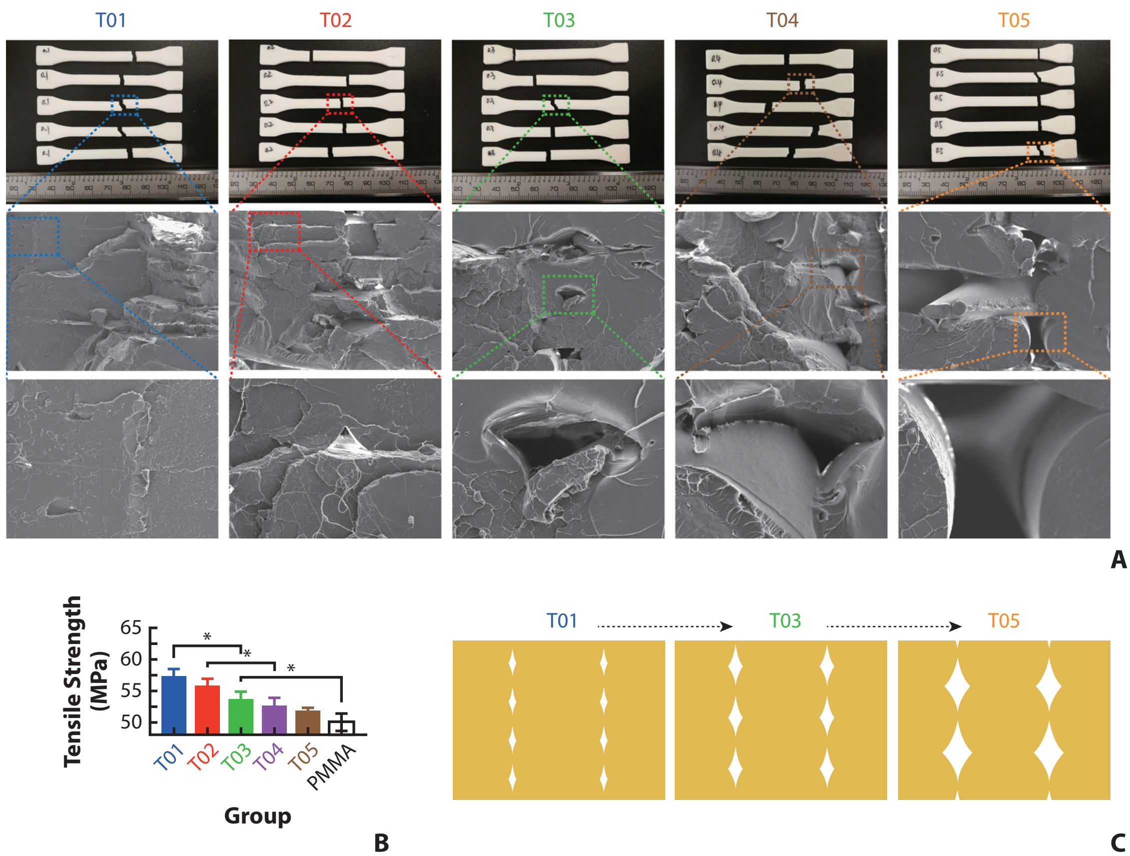

Figure 4. Fracture results of tensile test. A, Digital photographs (top row) and SEM images (original magnification middle row ×100; bottom row ×500) for 5 different layer thicknesses. B, Tensile strength bar chart of 5 PLA test groups and PMMA control group. Error bar represents standard deviation, *P<.05. C, Explanation of mechanism: with decreased layer thickness, conjoined portion between adjacent layers compactly fused, holes present in whole material decreased, cross-sectional area and tensile strength increased. PLA, polylactic acid; PMMA, polymethylmethacrylate; SEM, scanning electron microscope.

no effect on printing accuracy, as the accuracy associated with the FDM technique was inadequate for acute angles; however, the layer thickness may modulate both printing time and cost.

The printing time is an important consideration for the production of 3D-printed trays. The present study confirmed that the printing time sharply increased as the thickness decreased. The printing time is longer than the design time and is readily controllable by altering the printing layer thickness and printing speed.[3] The results of this study indicate that a mid-range printing layer thickness is optimal for the 3D-printed custom trays, which is applicable to tray fabrication. Limitations of the present study included that only an FDM 3D printer and PLA tray material were assessed. Many other printers and materials can be used to fabricate 3D-printed custom trays.[1,2] Additionally, the effects of printing orientation on the mechanical properties of trays were not evaluated. Further studies are needed to explore the effects of printing parameters on the mechanical properties of various 3D printers and tray materials.

CONCLUSIONS

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

1. As the layer thickness is increased, the adhesive capacity between the impression material and the printed trays initially increased and then decreased.
2. The same increase in layer thickness resulted in a decrease in the strength of a tray and an increase in time efficiency but had little effect on the dimensional accuracy.
3. The optimal printing layer for 3D-printed custom trays was found to be in the mid-range of the examined specimens.

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