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Comparative Evaluation of Surface Roughness of Direct-Printed 3D and Thermoformed Orthodontic Aligners: An Ex Vivo Study

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ABSTRACT:

Background: Clear aligner therapy has become an integral component of contemporary orthodontics owing to its superior esthetics, patient comfort, and removability. The long-term clinical performance of aligners depends not only on their mechanical properties but also on their surface characteristics. Surface roughness influences bacterial adhesion, biofilm accumulation, optical transparency, and patient comfort. Recently introduced direct three-dimensional (3D)-printed aligners have eliminated the conventional thermoforming process; however, evidence regarding their surface integrity after intraoral use remains limited.

Objective: To compare the surface roughness characteristics of direct-printed 3D aligners and thermoformed orthodontic aligners before and after clinical intraoral use.

Materials and Methods: An ex vivo comparative study was conducted using three commercially available aligner materials: polyethylene terephthalate glycol-modified (PET-G; Erkodur), thermoplastic polyurethane (TPU; Zendura FLX), and directly printed aligners fabricated from Graphy TA-28 resin. Twenty aligners were included in each group. Surface roughness was evaluated before intraoral use (control) and after clinical use using a non-contact optical profilometer. The evaluated parameters included arithmetic mean height (Sa), root mean square height (Sq), maximum surface height (Sz), profile roughness (Ra), root mean square roughness (Rq), total profile height (Rt), valley void volume (Vvv), and core void volume (Vvc). Statistical analysis was performed using the Kruskal–Wallis test for intergroup comparisons and the Wilcoxon signed-rank test for intragroup comparisons. Statistical significance was established at $p < 0.05$.

Results: Significant differences in surface roughness were observed among the three aligner materials. Following intraoral use, PET-G and TPU aligners demonstrated a significant reduction in most surface roughness parameters, indicating a polishing effect produced by the oral environment. In contrast, direct-printed aligners exhibited significantly higher surface roughness values after clinical use, suggesting increased susceptibility to surface degradation. Intergroup comparisons revealed significantly greater roughness values in direct-printed aligners than in thermoformed materials.

Conclusion: Surface characteristics differed significantly between thermoformed and direct-printed aligners. Thermoformed PET-G and TPU aligners exhibited smoother surfaces after intraoral use, whereas direct-printed aligners demonstrated increased surface roughness that may favor plaque accumulation and biofilm formation. Further improvements in printing technology and resin formulation are required before direct-printed aligners can consistently achieve the surface quality of conventional thermoformed aligners.

INTRODUCTION

Clear aligner therapy has transformed contemporary orthodontic practice by providing an esthetic and comfortable alternative to conventional fixed appliances[1]. Over the last two decades, advances in digital orthodontics have enabled virtual treatment planning, computer-aided design, and customized appliance fabrication, resulting in increased acceptance of clear aligners among both clinicians and patients. Besides superior esthetics, removable aligners facilitate improved oral hygiene, reduced dietary restrictions, and enhanced patient comfort, making them particularly attractive for adult orthodontic treatment. These advantages have contributed to the rapid expansion of clear aligner therapy worldwide. [1], [2]

Conventional clear aligners are fabricated by thermoforming transparent thermoplastic sheets over three-dimensional printed dental models. Polyethylene terephthalate glycol-modified (PET-G) and thermoplastic polyurethane (TPU) remain the most frequently used materials because of their favorable optical properties, flexibility, dimensional stability, and biocompatibility. However, the thermoforming process itself alters material thickness and may introduce dimensional inconsistencies that influence the biomechanical performance of aligners. (1,3)

Recent advances in additive manufacturing have introduced direct three-dimensional (3D) printing of orthodontic aligners. Unlike conventional manufacturing, direct printing eliminates the intermediate thermoforming step and allows fabrication of aligners directly from digital designs (4). This technology offers several potential advantages, including reduced material waste, improved dimensional accuracy, simplified laboratory workflow, rapid manufacturing, and the possibility of fabricating aligners with variable thickness according to biomechanical requirements. Nevertheless, direct-printing technology is relatively new, and its clinical performance requires comprehensive evaluation before widespread clinical adoption. [5]

Apart from force delivery, the surface characteristics of orthodontic aligners play a crucial role in their clinical success. Surface roughness influences optical transparency, patient comfort, wear resistance, microbial adhesion, and biofilm formation[6]. Rough surfaces provide favorable niches for bacterial colonization and plaque retention, increasing the risk of enamel demineralization, gingival inflammation, and unpleasant odor during orthodontic treatment. Therefore, maintaining a smooth aligner surface throughout clinical service is essential for preserving both appliance aesthetics and oral health.[7]

The intraoral environment subjects aligners to numerous physical and chemical challenges. Continuous exposure to saliva, dietary acids, thermal fluctuations, masticatory forces, and routine insertion and removal can modify the surface topography of thermoplastic materials. [8] Such alterations may either polish the material surface through mechanical wear or increase surface irregularities because of abrasion, hydrolytic degradation, and material fatigue. The magnitude of these changes depends largely on the chemical composition of the aligner material and its resistance to intraoral aging. [9]

Several investigations have reported that thermoformed aligners undergo measurable changes in surface morphology after clinical use. Recent studies have also demonstrated that directly printed aligners may exhibit different surface behavior owing to their layer-by-layer manufacturing process and unique polymerization characteristics[9]. Although direct printing eliminates thickness variations associated with thermoforming, the printed surface may contain microscopic layer lines and resin-related irregularities that could influence long-term clinical performance. Consequently, understanding the surface behavior of different aligner materials following intraoral service has become increasingly important.[9]

Despite growing interest in directly printed aligners, comparative evidence regarding their surface roughness after clinical use remains limited[10]. Most available studies have focused primarily on mechanical properties or dimensional accuracy, whereas fewer investigations have evaluated clinically relevant surface characteristics under intraoral conditions[11]. Furthermore, comparisons between conventional thermoformed materials and newly introduced direct-printing resins remain scarce.[11]

Therefore, the present ex vivo study aimed to compare the surface roughness characteristics of two thermoformed aligner materials—polyethylene terephthalate glycol-modified (PET-G) and thermoplastic polyurethane (TPU)—with directly printed aligners fabricated using Graphy TA-28 resin before and after clinical intraoral use. The null hypothesis was that no significant differences would exist in surface roughness among the evaluated aligner materials following intraoral service.

MATERIALS AND METHODS

Study design

This ex vivo comparative study evaluated changes in the surface roughness of thermoformed and direct-printed orthodontic aligners following intraoral use. The study was conducted in the Department of Orthodontics and Dentofacial Orthopaedics, Vinayaka Mission's Sankarachariyar Dental College and Hospital, Salem, India. Surface roughness analysis was performed at the Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai. Ethical approval for the study was obtained from the Institutional Research Committee (IRC No. IRC/07062024/T/5). The methodology was derived from the experimental protocol described in the thesis while focusing exclusively on the ex vivo surface roughness component.

Sample size

The sample size was estimated using G*Power software based on data from previous studies evaluating surface roughness changes in clear aligners. Considering a confidence level of 95%, statistical power of 80%, and a significance level of 5%, a minimum sample size of 10 aligners per group was calculated.

A total of 30 aligners were included and divided into three groups: (Table 1)

- **Group I:** Polyethylene terephthalate glycol-modified (PET-G; Erkodur®, Erkodent, Germany)
- **Group II:** Thermoplastic polyurethane (TPU; Zendura FLX®, Bay Materials LLC, USA)
- **Group III:** Direct-printed aligners fabricated using Graphy TA-28 photocurable resin (Graphy Inc., South Korea)

Each group consisted of 10 aligners.

Fabrication of aligners

Digital impressions were obtained using an intraoral scanner to generate standard tessellation language (STL) files. For the thermoformed groups, dental models were produced from the STL files, and aligners were fabricated using a pressure thermoforming unit according to the manufacturers' recommendations. Following thermoforming, the aligners were trimmed, finished, and inspected to ensure complete adaptation to the dental models.

For the direct-printed group, aligners were designed digitally using Maestro software (Version 6.0). Within the software, individual teeth were segmented to allow independent manipulation. Following segmentation, staging of tooth movements was carried out according to the prescribed treatment objectives.

Upon completion of digital treatment planning, the finalized models corresponding to each stage were exported for fabrication. A total of 10 aligners were fabricated using TA28 aligner resin through a Uniz NBEE 3D printing system (UNIZ Technology LLC, San Diego).

The printed aligners were then centrifuged using a Tera Spinner (Graphy) at 1,000 rpm for 5–6 minutes to remove excess resin. Subsequently, they underwent post-curing in a Tera Harz nitrogen curing chamber (Graphy, Seoul, Korea) to ensure complete polymerization.

Support structures were removed, and the aligners were trimmed and finished to obtain standardized specimens. After a three-day intraoral wear period, the aligners were retrieved for surface analysis.

Clinical protocol

The fabricated aligners were delivered to patients undergoing clear aligner therapy. Each aligner was worn according to the prescribed clinical protocol for three days. Patients were instructed to wear the aligners for 20–22 hours per day and to remove them only during meals and oral hygiene procedures. Standard oral hygiene instructions were provided to all participants, and no abrasive cleaning agents were permitted during the study period to minimize variability in surface alterations.

After completion of the clinical wear period, the aligners were retrieved, rinsed thoroughly with distilled water to remove saliva and loose debris, gently air-dried, and stored under standardized laboratory conditions until surface evaluation.

Surface roughness analysis

Surface characterization was performed using a non-contact three-dimensional optical profilometer, which enables high-resolution quantitative evaluation of surface topography without damaging the specimens. Measurements were performed under identical environmental conditions by a single calibrated examiner to eliminate operator-related variability.

For each aligner, the labial surface corresponding to the maxillary central incisor region was selected because this area is clinically important and experiences consistent intraoral exposure. Three separate scans were obtained from each specimen, and the average value was considered for statistical analysis.

The following three-dimensional roughness parameters were recorded according to ISO 25178 standards:

- **Sa (µm):** Arithmetic mean surface height
- **Sq (µm):** Root mean square surface height
- **Sz (µm):** Maximum surface height

In addition, two-dimensional profile roughness parameters were measured according to ISO 4287:

- **Ra (µm):** Arithmetic mean roughness
- **Rq (µm):** Root mean square roughness
- **Rt (µm):** Total profile height

Functional volume parameters representing the surface's fluid-retention characteristics were also evaluated:

- **Vvc:** Core void volume
- **Vvv:** Valley void volume

Surface roughness measurements were obtained before intraoral use (control) and after clinical retrieval to determine the effect of oral aging on each aligner material.

Outcome measures

The primary outcome of the study was the change in surface roughness following intraoral use.

Secondary outcomes included:

1. Comparison of baseline surface roughness among the three aligner materials.
2. Evaluation of changes in individual roughness parameters after clinical use.
3. Intergroup comparison of the magnitude of roughness changes following intraoral aging.

Statistical analysis

Data analysis was performed using IBM SPSS Statistics software (IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro–Wilk test. Since the roughness parameters did not demonstrate normal distribution, non-parametric statistical tests were employed.

Intergroup comparisons of baseline surface roughness were performed using the **Kruskal–Wallis test**. Pairwise comparisons were carried out using the **Bonferroni-adjusted post hoc test** when statistically significant differences were detected.

Changes in surface roughness within each group before and after intraoral use were analyzed using the **Wilcoxon signed-rank test**. Differences in the mean change among the three materials were evaluated using the Kruskal–Wallis test followed by Bonferroni correction for multiple comparisons.

All statistical tests were two-tailed, and a **p-value <0.05** was considered statistically significant.

Results

A total of 30 aligners (10 per group) were included in the surface roughness analysis. Baseline (control) and post-clinical surface characteristics were evaluated using non-contact optical profilometry. The surface roughness parameters analyzed included three-dimensional parameters (Sa, Sq, and Sz), two-dimensional profile parameters (Ra, Rq, and Rt), and functional volume parameters (Vvc and Vvv). Intergroup comparisons were performed using the Kruskal–Wallis test, while intragroup changes following intraoral use were analyzed using the Wilcoxon signed-rank test. Bonferroni post hoc analysis was performed for pairwise comparisons where appropriate.

RESULTS

Surface roughness analysis demonstrated significant differences among PET-G, TPU, and direct-printed aligners both before and after intraoral use. Baseline comparison using the Kruskal–Wallis test showed statistically significant intergroup differences for all evaluated parameters (Sa, Sq, Sz, Ra, Rq, Rt, Vvv, and Vvc) ($\chi^2 = 19.000$, $p < 0.001$), confirming that the three aligner materials possessed distinct inherent surface topographies before clinical use.(Table 2) PET-G exhibited the highest baseline roughness values (Sa = 66.81 μm, Sq = 158.60 μm, Sz = 4778.71 μm, Ra = 91.88 μm, Rq = 145.19 μm, Rt = 2809.45 μm), whereas the direct-printed aligners demonstrated the lowest baseline profile roughness (Ra = 0.1409 μm, Rq = 0.2111 μm, Rt = 1.4249 μm). TPU exhibited intermediate characteristics, with low areal roughness (Sa = 0.1435 μm; Sq = 0.8956 μm) but comparatively higher profile roughness (Ra = 86.73 μm; Rt = 2237.39 μm).

Following three days of intraoral use, PET-G aligners exhibited significant reductions in profile roughness parameters. Ra decreased from 91.88 μm to 51.89 ± 18.40 μm ($Z = -2.023$, $p = 0.043$), Rq decreased from 145.19 μm to 76.44 ± 27.06 μm ($Z = -2.023$, $p = 0.043$), and Rt decreased from 2809.45 μm to 903.01 ± 498.70 μm ($Z = -2.023$, $p = 0.043$). No statistically significant changes were observed for Sa, Sq, Sz, Vvv, or Vvc ($p > 0.05$)(Table 3).

Similarly, TPU aligners demonstrated significant reductions in several roughness parameters after clinical use. Sq decreased from 0.8956 μm to 0.4294 ± 0.1175 μm (Z = –2.023, p = 0.043), Sz decreased from 38.12 μm to 19.55 ± 10.71 μm (Z = –2.023, p = 0.043), and Ra decreased from 86.73 μm to 34.72 ± 33.58 μm (Z = –2.023, p = 0.043). In contrast, Vvc increased significantly from 0.0837 to 0.1705 ± 0.0756 μm³/μm² (Z = –2.032, p = 0.042). Changes in Sa, Rq, Rt, and Vvv were not statistically significant (Table 4).

The direct-printed aligners exhibited a distinct pattern of surface alteration after intraoral service. Sa decreased significantly from 0.4460 μm to 0.3276 ± 0.0512 μm (Z = –2.803, p = 0.005), and Sq decreased from 0.8397 μm to 0.6195 ± 0.1096 μm (Z = –2.803, p = 0.005). However, Sz increased significantly from 8.74 μm to 19.90 ± 12.29 μm (Z = –2.803, p = 0.005), indicating the development of larger peak-to-valley surface irregularities. Rt also increased markedly from 1.42 μm to 186.70 ± 388.24 μm (Z = –2.497, p = 0.013). Vvv decreased significantly from 0.0680 to 0.0503 ± 0.0137 μm³/μm² (Z = –2.497, p = 0.013), whereas Vvc increased substantially from 0.0694 to 0.4872 ± 0.0932 μm³/μm² (Z = –2.803, p = 0.005). Ra and Rq did not demonstrate statistically significant differences after clinical use(Table 5).

Intergroup comparison of the mean changes after clinical service demonstrated significant differences among the three materials. PET-G exhibited the greatest reduction in Sa (Δ = –24.76 μm) and Sq (Δ = –18.78 μm), whereas the direct-printed aligners showed comparatively smaller reductions in Sa (Δ = –0.118 μm) and Sq (Δ = –0.220 μm) but a positive increase in Sz (Δ = +11.17 μm). Analysis of variance demonstrated significant differences among the groups for Sa (p < 0.001), Sq (p < 0.001), and Sz (p = 0.002), and Bonferroni post hoc analysis confirmed significant pairwise differences between thermoformed and direct-printed aligners(Table 6).

DISCUSSION

The present ex vivo investigation evaluated the influence of short-term intraoral aging on the surface characteristics of thermoformed PET-G, thermoformed TPU, and directly printed TA-28 orthodontic aligners. The findings demonstrated that both the manufacturing technique and material composition significantly influenced surface topography following clinical service. Although all materials exhibited measurable alterations after one week of intraoral use, the pattern of change differed considerably among the three groups.

The baseline analysis demonstrated significant intergroup differences for all eight surface roughness parameters (χ^2 = 19.000, p < 0.001). PET-G exhibited the highest initial profile roughness, while the direct-printed resin demonstrated the lowest baseline roughness values. These observations reflect the intrinsic differences between thermoformed thermoplastic sheets and additively manufactured photopolymer resins. Industrial extrusion of PET-G sheets produces characteristic surface irregularities associated with thermoforming, whereas stereolithographic printing generates comparatively smoother surfaces immediately after fabrication despite its layer-by-layer manufacturing process.

Following intraoral service, PET-G aligners exhibited significant reductions in Ra, Rq, and Rt, suggesting a polishing effect during clinical use. Ra decreased by approximately 43%, while Rt decreased by nearly 68%, indicating considerable smoothing of profile irregularities. These findings suggest that repeated insertion and removal, masticatory contact, and continuous exposure to saliva may preferentially abrade superficial asperities without substantially altering the overall three-dimensional surface architecture[13]. Similar observations have been reported by Eslami et al., [9] who demonstrated reduced surface roughness in thermoformed Invisalign aligners following one week of intraoral use, attributing the findings to physiological polishing within the oral environment.

TPU aligners demonstrated an even more favorable surface response. Significant reductions were observed in Sq, Sz, and Ra, while the increase in Vvc indicated alteration of the internal surface texture rather than gross surface deterioration. The reduction of Sz from 38.12 μm to 19.55 μm represents almost a 50% decrease in maximum surface height, supporting the excellent wear resistance of thermoplastic polyurethane. TPU possesses greater elasticity and resilience than PET-G, allowing deformation under functional loading without permanent surface damage. These findings support previous investigations demonstrating superior wear resistance and flexibility of polyurethane-based orthodontic materials.

Unlike the thermoformed materials, the direct-printed TA-28 aligners demonstrated a mixed pattern of surface alteration. Although Sa and Sq decreased significantly, indicating localized smoothing of the average surface, the simultaneous increase in Sz (8.74 to 19.90 μm) and Rt (1.42 to 186.70 μm) suggests the formation of isolated deep defects or prominent surface peaks.

The marked increase in Vvc from 0.0694 to 0.4872 µm³/µm² further indicates substantial alteration of the core surface morphology. These findings imply that intraoral aging of printed resins is characterized less by uniform abrasion and more by heterogeneous surface degradation, including possible resin delamination, micro-crack formation, or localized wear.

The present observations closely agree with the study of Koletsi et al., [14] who demonstrated significantly greater surface deterioration in clinically retrieved 3D-printed aligners compared with thermoformed Invisalign appliances. Likewise, Eslami et al. [14] reported increased surface roughness and porosity of directly printed TC-85 aligners after one week of clinical use, suggesting increased susceptibility to bacterial colonization and biofilm formation. The present study extends these findings by quantitatively demonstrating significant increases in Sz, Rt, and Vvc despite reductions in average roughness parameters.

From a clinical perspective, increased peak-to-valley height and core void volume may be more relevant than average roughness alone. Deep surface defects can serve as protected niches for bacterial adhesion and biofilm maturation, potentially compromising oral hygiene during aligner therapy. Although direct-printed aligners offer substantial advantages in digital workflow, customization, and manufacturing efficiency, their long-term clinical success depends on maintaining adequate surface integrity throughout the period of intraoral use.

The findings of this study should be interpreted within certain limitations. Only one commercially available direct-printing resin and two thermoformed materials were evaluated, and the duration of intraoral aging was limited to three days. Furthermore, optical profilometry evaluates surface topography but does not directly assess bacterial adhesion or clinical biofilm accumulation. Future investigations incorporating scanning electron microscopy, confocal microscopy, microbiological assessment, and longer clinical observation periods are required to establish the relationship between surface degradation and clinical performance.

Overall, the present study indicate more favorable surface stability during short-term intraoral service than directly printed TA-28 aligners. While direct-printing technology continues to evolve rapidly, further optimization of printable resin formulations and post-processing protocols appears necessary before their surface performance consistently matches that of established thermoformed aligner materials.

Table 1

S.NO	PRODUCT NAME	MANUFACTURER	COMPOSITION	THICKNESS (mm)
1	Erkodur	Erkodent erich Kopp, Germany.	PET-G	0.80mm
2	Zendura FLX	Bay materials LLC, Fremont, California, USA.	TPU	0.80mm
3	Tera Harz – Direct printed aligner	Graphy Inc, Seoul, South Korea.	TA- 28	0.80mm

Table 2. Baseline Surface Roughness Characteristics of PET-G, TPU and Direct Printed Aligners

Parameter	PET-G(n=10) (Mean ± SD)	TPU(n=10) (Mean ± SD)	DPA(n=10) (Mean ± SD)	χ^2 value	p value
Sa (Control)	66.8138 ± 0.0000 µm	0.1435 ± 0.0000 µm	0.4460 ± 0.0000 µm	19.000	**<0.001***
Sq (Control)	158.6033 ± 0.0000 µm	0.8956 ± 0.0000 µm	0.8397 ± 0.0000 µm	19.000	**<0.001***
Sz (Control)	4778.7056 ± 0.0000 µm	38.1155 ± 0.0000 µm	8.7357 ± 0.0000 µm	19.000	**<0.001***

Parameter	PET-G(n=10) (Mean ± SD)	TPU(n=10) (Mean ± SD)	DPA(n=10) (Mean ± SD)	χ^2 value	p value
Ra (Control)	91.8824 ± 0.0000 µm	86.7285 ± 0.0000 µm	0.1409 ± 0.0000 µm	19.000	**<0.001***
Rq (Control)	145.1925 ± 0.0000 µm	126.5109 ± 0.0000 µm	0.2111 ± 0.0000 µm	19.000	**<0.001***
Rt (Control)	2809.4534 ± 0.0000 µm	2237.3899 ± 0.0000 µm	1.4249 ± 0.0000 µm	19.000	**<0.001***
Vvv (Control)	0.0091 ± 0.0000 µm³/µm²	0.0420 ± 0.0000 µm³/µm²	0.0680 ± 0.0000 µm³/µm²	19.000	**<0.001***
Vvc (Control)	0.0865 ± 0.0000 µm³/µm²	0.0837 ± 0.0000 µm³/µm²	0.0694 ± 0.0000 µm³/µm²	19.000	**<0.001***

Statistically significant at $p < 0.05$.

Table 3: Comparison of Surface Roughness Parameters Between Control and Clinical Conditions for PET-G Using the Wilcoxon Signed-Rank Test

Parameter	Control Mean ± SD	Clinical Mean ± SD	Z value	p value
Sa	66.8138 ± 0.0000 µm	42.0544 ± 40.5347 µm	-0.944	0.345
Sq	158.6033 ± 0.0000 µm	139.8189 ± 167.7919 µm	-0.405	0.686
Sz	4778.7056 ± 0.0000 µm	3168.8001 ± 2913.5411 µm	-0.674	0.500
Ra	91.8824 ± 0.0000 µm	51.8879 ± 18.4032 µm	-2.023	**0.043***
Rq	145.1925 ± 0.0000 µm	76.4411 ± 27.0559 µm	-2.023	**0.043***
Rt	2809.4534 ± 0.0000 µm	903.0060 ± 498.7035 µm	-2.023	**0.043***
Vvv	0.0091 ± 0.0000 µm³/µm²	0.0212 ± 0.0104 µm³/µm²	-1.753	0.080
Vvc	0.0865 ± 0.0000 µm³/µm²	0.0929 ± 0.0363 µm³/µm²	-0.135	0.893

***Statistically significant ($p \leq 0.05$)**

Table 4: Comparison of Surface Roughness Parameters Between Control and Clinical Conditions for TPU Using the Wilcoxon Signed-Rank Test

Parameter	Control Mean ± SD	Clinical Mean ± SD	Z value	p value
Sa	0.1435 ± 0.0000 µm	0.1633 ± 0.0428 µm	-0.944	0.345
Sq	0.8956 ± 0.0000 µm	0.4294 ± 0.1175 µm	-2.023	**0.043***
Sz	38.1155 ± 0.0000 µm	19.5469 ± 10.7095 µm	-2.023	**0.043***
Ra	86.7285 ± 0.0000 µm	34.7189 ± 33.5816 µm	-2.023	**0.043***
Rq	126.5109 ± 0.0000 µm	64.5386 ± 75.1806 µm	-1.483	0.138
Rt	2237.3899 ± 0.0000 µm	846.1263 ± 1142.4024 µm	-1.753	0.080
Vvv	0.0420 ± 0.0000 µm³/µm²	0.0422 ± 0.0130 µm³/µm²	-0.406	0.684
Vvc	0.0837 ± 0.0000 µm³/µm²	0.1705 ± 0.0756 µm³/µm²	-2.032	**0.042***

***Statistically significant ($p \leq 0.05$)**

Table 5: Comparison of Surface Roughness Parameters Between Control and Clinical Conditions for DPA Using the Wilcoxon Signed-Rank Test

Parameter	Control Mean ± SD	Clinical Mean ± SD	Z value	p value
Sa	0.4460 ± 0.0000 µm	0.3276 ± 0.0512 µm	-2.803	**0.005***
Sq	0.8397 ± 0.0000 µm	0.6195 ± 0.1096 µm	-2.803	**0.005***
Sz	8.7357 ± 0.0000 µm	19.9047 ± 12.2866 µm	-2.803	**0.005***
Ra	0.1409 ± 0.0000 µm	16.7757 ± 34.9754 µm	-0.866	0.386
Rq	0.2111 ± 0.0000 µm	22.4824 ± 46.7489 µm	-0.866	0.386

Parameter	Control Mean ± SD	Clinical Mean ± SD	Z value	p value
Rt	1.4249 ± 0.0000 μm	186.7021 ± 388.2381 μm	-2.497	**0.013***
Vvv	0.0680 ± 0.0000 $\mu m^3/\mu m^2$	0.0503 ± 0.0137 $\mu m^3/\mu m^2$	-2.497	**0.013***
Vvc	0.0694 ± 0.0000 $\mu m^3/\mu m^2$	0.4872 ± 0.0932 $\mu m^3/\mu m^2$	-2.803	**0.005***

***Statistically significant ($p \leq 0.05$)**

Table6: Intergroup Comparison of Mean Difference in Surface Roughness Parameters among aligner materials after clinical Conditions using Bonferroni Post Hoc Test

Parameter	PET-G Δ Mean	TPU Δ Mean	DPA Δ Mean	ANOVA p value	TPU vs PET-G (p)	TPU vs DPA (p)	PET-G vs DPA (p)
Sa	−24.7594	+0.0198	−0.1184	<0.001	<0.001	<0.001	<0.001
Sq	−18.7844	−0.4662	−0.2202	<0.001	<0.001	<0.001	<0.001
Sz	−1609.9055	−18.5686	+11.1690	0.002	0.008	1.000	0.002
Ra	−39.9945	−52.0096	+16.6348	0.148	1.000	0.939	0.173
Rq	−68.7514	−61.9723	+22.2713	<0.001	<0.001	<0.001	<0.001
Rt	−1906.4474	−1391.2636	+185.2772	<0.001	<0.001	<0.001	<0.001
Vvv	+0.0121	+0.0002	−0.0177	0.003	0.057	0.796	0.002
Vvc	+0.0064	+0.0868	+0.4178	<0.001	<0.001	<0.001	<0.001

***Statistically significant ($p \leq 0.05$)**

CLINICAL IMPLICATIONS

The surface quality of orthodontic aligners plays an important role in patient comfort, esthetics, and oral hygiene maintenance. The smoother surface characteristics observed in thermoformed PET-G and TPU aligners after clinical use may reduce bacterial adhesion and improve long-term clinical performance. Conversely, the localized surface deterioration observed in direct-printed aligners highlights the need for careful clinical monitoring, meticulous aligner hygiene, and continued optimization of additive manufacturing technologies before their routine clinical application

CONCLUSION

Within the limitations of this ex vivo study, the surface characteristics of orthodontic aligners were found to be significantly influenced by both the material composition and the fabrication technique. Thermoformed PET-G and TPU aligners exhibited favorable changes in surface topography following one week of intraoral use, with significant reductions in profile roughness parameters, suggesting a polishing effect associated with functional wear in the oral environment. Among the thermoformed materials, TPU demonstrated the most stable surface characteristics, indicating superior resistance to surface degradation.

In contrast, direct-printed TA-28 aligners exhibited a heterogeneous pattern of surface alteration. Although average areal roughness parameters (Sa and Sq) decreased after clinical use, significant increases in maximum surface height (Sz), total profile height (Rt), and core void volume (Vvc) indicated the development of localized surface defects and structural irregularities. These changes may predispose the aligner surface to increased plaque accumulation, bacterial adhesion, and long-term material degradation.

Overall, the findings suggest that current thermoformed aligner materials maintain better surface integrity during short-term intraoral use than the evaluated direct-printed aligner resin. Continued refinement of printable resin formulations, printing resolution, and post-processing protocols is required before direct-printed aligners can consistently achieve surface characteristics comparable with conventional thermoformed aligners.

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