Comparison of Marginal Fit and Mechanical Performance of Three-unit Implant-supported Fixed Dental Prostheses Fabricated Using a Fully Digital Workflow and Conventional Workflow

Shi Qing SHI[1#], Dan Ni GUO[1#], Mo Di HENG[2], Bo CHEN[3], Shao Xia PAN[1]

Objective: *To compare the marginal fit and mechanical performance of three-unit implant-supported fixed dental prostheses (ISFDPs) fabricated using fully digital and conventional workflows.*

Methods: *Three-unit ISFDP specimens in this study simulated the restoration of three consecutively missing teeth in the mandibular posterior region. Twenty-four specimens were divided into three groups: the zirconia fully digital (ZFD) group received zirconia ISFDPs fabricated using a fully digital workflow; the polyetherketoneketone fully digital (PFD) group received polyetherketoneketone (PEKK) ISFDPs fabricated using a fully digital workflow; and the zirconia control (ZC) group received zirconia ISFDPs fabricated using a conventional workflow. Marginal gaps between restorations and abutments during passive and active fit were measured, and initial screw loosening torque values of restorations were recorded. After undergoing 1,200,000 cycles of vertical loading, the restorations were reassessed for marginal gaps and loosening torque values.*

Results: *Marginal fit under passive and active fit in the ZFD group showed no significant difference in relation to the ZC group. Marginal gaps in the PFD group (134.39 ± 41.13 µm) under passive fit were significantly larger than in the ZFD group, and decreased significantly under active fit (22.28 ± 10.45 µm). No significant difference in marginal fit was observed before and after cyclic loading in all groups. No significant difference was found in loosening torque change between the ZFD and ZC groups, whereas the change in the PFD group (median −2.13%, Q_{25} −3.30%/Q_{75} 0.28%) was significantly lower than in the ZC group (median −5.83%, Q_{25} −8.46%/Q_{75} −3.75%).*

Conclusion: *Three-unit ISFDPs fabricated using fully digital and conventional workflows exhibit similar marginal fit and mechanical performance. Additionally, PEKK ISFDPs demonstrate clinically acceptable marginal fit and mechanical performance.*

Keywords: *cyclic loading, fixed prostheses, fully digital workflow, marginal fit, polyetherketoneketone*

Chin J Dent Res 2025;28(4):277–286; doi: 10.3290/j.cjdr.b6745493

1 Department of Prosthodontics, Peking University School and Hospital of Stomatology & National Center for Stomatology & National Clinical Research Center for Oral Diseases & National Engineering Research Center of Oral Biomaterials and Digital Medical Devices & Beijing Key Laboratory of Digital Stomatology & NHC Key Laboratory of Digital Stomatology & NMPA Key Laboratory for Dental Materials, Beijing, P.R. China

2 Dental laboratory, Peking University School and Hospital of Stomatology, Beijing, P.R. China

3 Department of Implantology, Peking University School and Hospital of Stomatology, Beijing, P.R. China

 # Equal contribution.

Corresponding authors: Dr Shao Xia PAN, Department of Prosthodontics, Peking University School and Hospital of Stomatology, No. 22 Zhongguancun South Avenue, Haidian District, Beijing 100081, P.R. China. Tel: 86-13011110951. Email: panshaoxia@vip.163.com;

Dr Bo CHEN, Department of Implantology, Peking University School and Hospital of Stomatology, No. 22 Zhongguancun South Avenue, Haidian District, Beijing 100081, P.R. China. Email: mdchenbo@yahoo.com

This study was supported by Dentsply Sirona, Mölndal, Sweden; the Clinical Research Foundation of Peking University School and Hospital of Stomatology (PKUSS-2023CRF501); and the Beijing Natural Science Foundation (no. L232146).

The model-free fully digital workflow for implant-supported fixed dental prostheses (ISFDPs) includes acquiring digital impressions through intraoral scanning (IOS) and fabricating restorations based on the digital data using CAD/CAM.[1] Compared to the model-based conventional workflow that relies on conventional impressions, the model-free, fully digital workflow offers greater efficiency, reduced costs and the potential to improve patient comfort and acceptance.[2-4] However, since the model-free fully digital workflow relies on the IOS system, clinical scepticism remains regarding its ability to produce digital impressions with reliable accuracy.[5]

In clinical practice, the accuracy of impressions can impact the marginal fit and mechanical performance of implant restorations significantly. Implant restorations with significant marginal discrepancies and poor mechanical performance increase the risk of biological and mechanical complications, such as microleakage, screw loosening, abutment fracture and implant fracture.[6-8] Absolute marginal fit is unattainable in clinical practice,[9,10] and a marginal discrepancy of 10 to 150 μm is generally considered acceptable.[11-14] Existing studies often employ in vitro cyclic loading to simulate oral chewing function, allowing for the assessment of implant restoration mechanical performance.[15-18]

Several clinical studies have shown that the marginal fit and mechanical performance of single implant restorations fabricated using a fully digital workflow are similar or even superior to those using a conventional workflow.[19,20] However, disagreement remains regarding the clinical application of the fully digital workflow in multi-unit implant restorations. Abduo et al[21] and Ellakany et al[22] both observed a decrease in the accuracy of digital scans with increasing span by comparing full-arch and short span scanning. For three-unit ISFDPs, Alsharbaty et al[23] and Alshawaf et al[24] demonstrated that the accuracy of digital impressions was lower than that of conventional impressions, while Schepke et al[25] and Hashemi et al[26] reported that their accuracy was similar.

In the model-free, fully digital workflow, prosthetic materials suitable for CAD/CAM milling include nickel-chromium alloys, titanium and zirconia.[27] Zirconia is recognised clinically as a reliable choice for posterior single crowns and three-unit ISFDPs due to its excellent mechanical properties, biocompatibility and aesthetic effects.[28-31] Recently, a novel polymeric material, polyetherketoneketone (PEKK), exhibits superior physical, mechanical and biological properties, making it potentially suitable for dental restorations.[32] Some studies have found that PEKK materials demonstrated better marginal fit[33-35] as well as higher fatigue limits and longer fatigue life[36] in fixed restorations than zirconia materials. These studies, however, only evaluated restorations on natural teeth and did not investigate implant restorations. There is a lack of studies comparing the marginal fit and mechanical performance of three-unit ISFDPs made from various materials and fabricated using different workflows. This in-vitro study aims to validate the feasibility of fabricating three-unit ISFDPs with two kinds of materials using the model-free fully digital workflow.

Materials and methods

In-vitro three-unit ISFDP specimen fabrication and grouping

According to the International Organization for Standardization (ISO) 14801:2016 standard, three-unit ISFDP specimens were fabricated. First, 24 self-curing acrylic resin (Denture BasePolymer; Nissin, Kyoto, Japan) blocks with dimensions of 4.0 × 2.0 × 2.0 cm were prepared. Two parallel implants (OsseoSpeed TX 4.0 × 11 mm; Astra Tech Implant System, Dentsply Sirona, Charlotte, NC, USA) were inserted vertically in each resin block to simulate the second premolar and second molar, and the distance between the implant axis was 20 mm. The abutments (20° UniAbutment, Astra Tech Implant System, diameter 3.5 mm, 20° apical taper, height 2.15 mm and rim height 1 mm) were connected to the implants with a torque of 20 Ncm. The 24 specimens were randomly divided into three groups, and 24 three-unit ISFDPs were designed and fabricated as follows (Fig 1).

In the zirconia fully digital (ZFD) group and PEKK fully digital (PFD) group, fully digital workflows were employed for the design and fabrication of three-unit ISFDPs. For the ZFD group, scan bodies (DESS Intraoral Scan Body on 20° UniAbutment; Dental Smart Solutions) were connected to the 20° UniAbutment, and an IOS system (TRIOS Standard-P11; 3Shape, Copenhagen, Denmark) was used to obtain the digital models (Fig 2a to c). The scan data were imported into CAD software (Exocad Dental CAD, v3.0; Exocad, Darmstadt, Germany). A three-unit ISFDP was designed virtually and transferred to the CAM system. Eight zirconia three-unit ISFDPs were fabricated using a five-axis computer numerical control dental milling machine (Organical Multi Milling System and Desktop 8S Mill; Organical CAD/CAM, Berlin, Germany), then the ISFDPs were finalised. The same workflow and milling machine were used in the PFD group to fabricate eight PEKK three-unit ISFDPs.

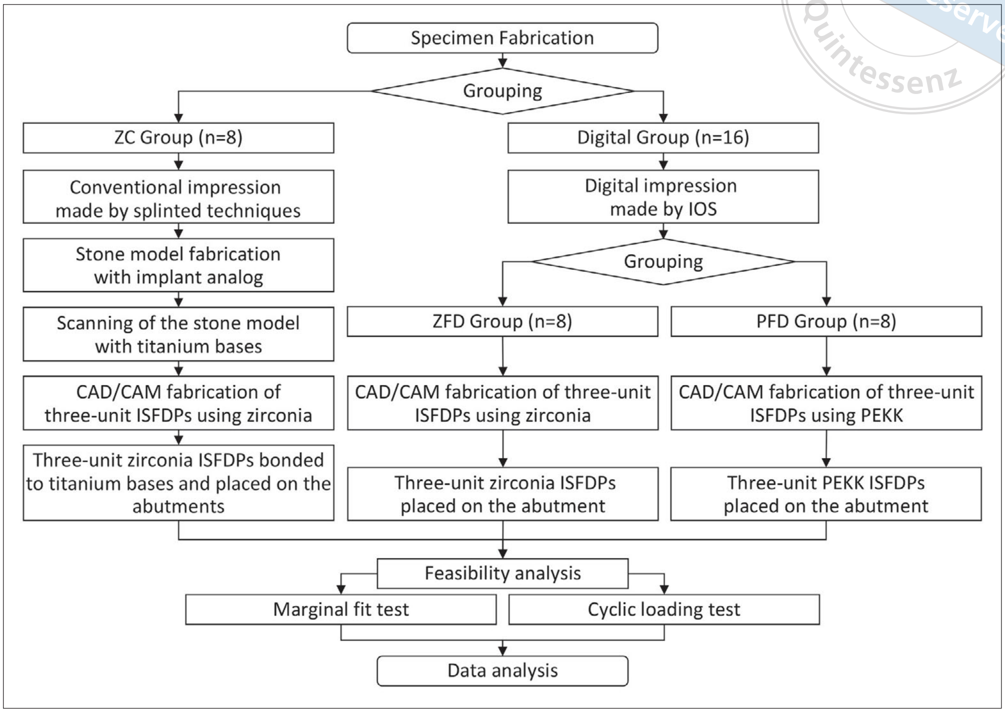

Fig 1 Study flowchart. PFD, PEKK fully digital group; ZC, zirconia control group; ZFD, zirconia fully digital group.

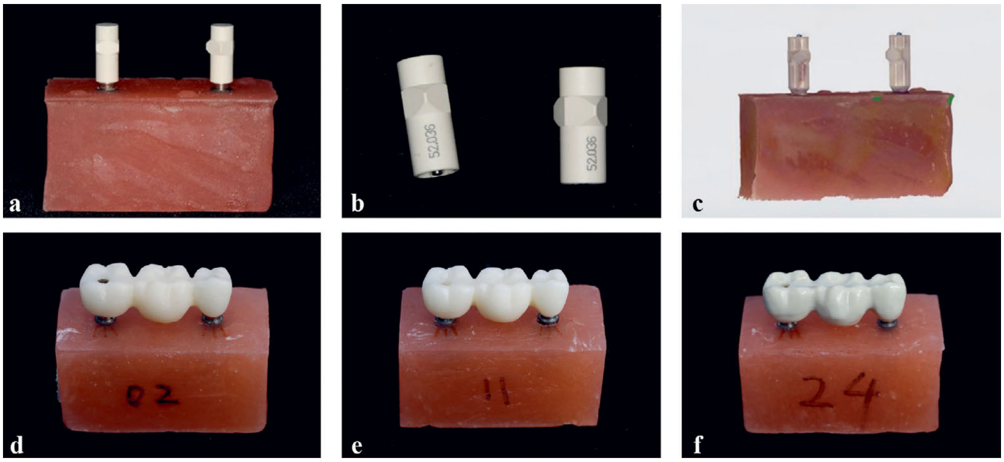

Fig 2a to f Process of obtaining digital models and three-unit ISFDPs in the three groups. ISFDP specimen (a); scanning rod (b); digital model (c); ZC group **(d)**; ZFD group (e); PFD group **(f)**.

In the zirconia control (ZC) group, the model-based conventional workflow was employed. The implant transfer posts (Implant Transfer; Astra Tech Implant System) were connected to the 20° UniAbutments and a conventional open-tray analogue impression was taken for each model with polyether impression material (3M Impregum Penta; 3M, St. Paul, MN, USA). The implant analogues were secured to the implant transfer posts. Type V gypsum casts (DieStone; Kulzer, Essen, Germany) were poured. The same scan bodies were then fixed onto the implant analogues, and the casts were digitalised using a laboratory scanner (3Shape D2000; 3Shape). Thereafter, the scan data were imported into the CAD software, a digital titanium base was virtually connected to each UniAbutment and the zirconia three-unit ISFDPs were designed virtually and transferred to the CAM system. Eight zirconia three-unit ISFDPs were fabricated. The zirconia three-unit ISFDPs were then bonded with the titanium base (Titanium Cylinder, Astra Tech Implant System, on 20° UniAbutment).

Subsequently, all three-unit ISFDPs were delivered onto the resin block specimen and connected to the 20° UniAbutments with screws torqued to 15 Ncm (Fig 2d to f).

Measurement of marginal fit of three-unit ISFDPs

The marginal gaps between the three-unit ISFDP and the implant abutment at the second molar were measured using a 3D laser scanning microscope with 0.001 μm

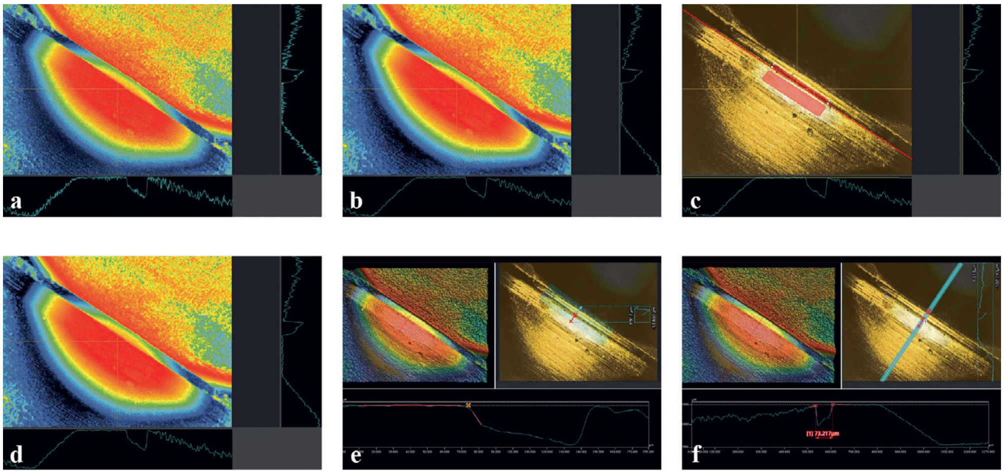

Fig 3a to f Measurement of the marginal gap of the three-unit ISFDP using the VK-X200. Raw elevation image (a); image after Gaussian smoothing (b); surface levelling (c); image after surface levelling **(d)**; edge line fitting (e); gap measurement **(f)**.

accuracy (10× objective lens, numerical aperture 0.95 with a violet laser source, 1.95 µm plane spatial resolution; VK-X200; Keyence) under three conditions. Under the no screw-tightening condition, the restoration screws were not tightened at either the second premolar or the second molar, and the marginal gap between the restoration and the abutment at the second molar was measured. Under the unilateral screw-tightening condition, only the restoration screws at the second premolar were tightened to 15 Ncm, and the marginal gap at the second molar was measured as an indicator to evaluate the passive fit of the three-unit ISFDPs.[12] Under the bilateral screw-tightening condition, the screws at both the second premolar and the second molar were tightened to 15 Ncm, and the marginal gap at the second molar was measured to evaluate the active fit of the three-unit ISFDPs.[13] For each three-unit ISFDP, six positions were selected on the buccal and lingual sides for gap measurement, namely mesio-lingual (ML), lingual (L), disto-lingual (DL), mesio-buccal (MB), buccal (B) and disto-buccal (DB). Subsequently, the data was imported into analysis software (VK-X Multi-File Analyzer v2.1.1.11; Keyence, Osaka, Japan) for measurement, as shown in Fig 3. The mean marginal gap between the restoration and the abutment on the buccal and lingual sides was calculated.

Cyclic loading test

The mechanical performance of the ISFDPs was evaluated using cyclic loading experiments. Before cyclic loading, all the screws of the three-unit ISFDPs were tightened with a torque of 15 Ncm to connect the second premolar and second molar to the abutments using a torque wrench. After 24 hours, the gaps between the restoration and the abutments on the buccal and lingual sides were measured using a 3D laser scanning microscope. Subsequently, the loosening torque values of the screws in the second premolar and second molar before cyclic loading were measured using an electronic torque meter (Torque Meter TQ-8800; Lutron, Coopersburg, PA, USA), denoted as V^l_0 (Fig 4a). Then, the screws of the three-unit ISFDPs were tightened again with a torque of 15 Ncm and the resin block with the ISFDPs was fixed on a loading platform of a cyclic loading instrument (ElectroPuls E1000; Instron, Norwood, MA, USA). A stainless-steel loading head (length 30 mm, width 8 mm, height 10 mm and loading surface radius 0.5 mm) was vertically applied to the central fossa of the occlusal surface of the three-unit ISFDPs for cyclic fatigue testing (Fig 4b and c), simulating clinical chewing conditions. This study followed the ISO 14801 standard and used a load of 50 N with a frequency of 15 Hz for 1,200,000 cyclic loading, simulating 5 years of clinical performance.[37-40] The machine stopped at 120,000, 600,000 and 1,200,000 loading cycles to monitor and record any mechanical complications such as screw loosening or abutment or implant fracture. After cyclic loading, the gaps between the restoration and the abutments on the buccal and lingual sides were measured again. Additionally, the torque values of the restoration screws were measured again and denoted as V^l_1. The formula for calculating the torque change (θ) is as follows:

$$\theta = \frac{V_1^l - V_0^l}{V_0^l} \times 100\%$$

Statistical analysis

The power analysis was based on a two-sample *t* test, and the estimated standard deviation (SD) is the pooled standard deviation estimated from prior studies. The data originated from an in vitro study assessing mar-

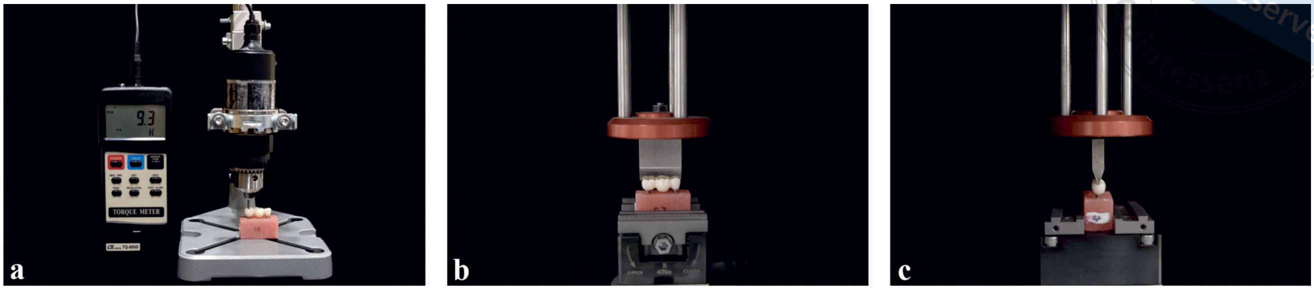

Fig 4a to c Cyclic loading test. An electronic torque meter was used to measure loosening torque values of restoration screws (a); frontal view of cyclic loading on the central fossa of the three-unit ISFDP (b); lateral view of cyclic loading on the central fossa of the three-unit ISFDP (c).

Table 1 Marginal gaps of ZC Group, ZFD Group and PFD Group under all screw-tightening conditions.

Group		No screw-tightening, mean ± SD (µm)	Unilateral screw-tightening, mean ± SD (µm)	Bilateral screw-tightening, mean ± SD (µm)
ZC	Buccal	77.65 ± 12.93	97.45 ± 21.25	38.91 ± 7.16
	Lingual	102.99 ± 15.03	97.55 ± 25.07	35.74 ± 15.03
	Mean	90.32 ± 11.90	97.50 ± 20.36	37.33 ± 8.44
ZFD	Buccal	48.44 ± 19.06	64.24 ± 40.99	41.00 ± 15.88
	Lingual	62.85 ± 46.74	65.20 ± 41.00	33.28 ± 18.15
	Mean	55.65 ± 25.13	64.72 ± 38.16	37.14 ± 11.09
PFD	Buccal	122.64 ± 25.59	137.49 ± 50.14	25.24 ± 12.05
	Lingual	143.51 ± 20.65	131.30 ± 34.99	19.32 ± 09.48
	Mean	133.07 ± 21.64	134.39 ± 41.13	22.28 ± 10.45

ginal gaps of three-unit ISFDPs fabricated using different techniques.[41] The sample size was eight per group, with a power of 80%.

All data were imported into statistical software (SPSS v27.0; IBM, Armonk, NY, USA) for descriptive statistical analysis. The normality of the data was assessed using Shapiro-Wilk tests, whereas the equality of variances was evaluated using a Levene test. Parametric tests and post-hoc pairwise comparison tests (Student-Newman-Keuls test) were conducted to compare the marginal gaps under three screw-tightening conditions in each group. An independent samples *t* test was employed to analyse the statistical differences in marginal fit among the groups. A repeated measures analysis of variance (ANOVA) was conducted to statistically analyse the marginal fit of the restoration before and after cyclic loading for the three groups. As the loosening torque change values were not normally distributed, a nonparametric Mann-Whitney U test was used to analyse the differences among the three groups. The significance level α was set at 5%.

Results

As shown in Table 1 and Fig 5, the marginal fit between the restoration and the abutment was found to differ significantly among the three groups under the three screw-tightening conditions ($P < 0.01$). Compared to the marginal gap (ZC group 90.32 ± 11.90 µm; ZFD group 55.65 ± 25.13 µm; PFD group 133.07 ± 21.64 µm) under the no screw-tightening condition, there was no significant increase in the gaps (ZC group 97.50 ± 20.36 µm; ZFD group 64.72 ± 38.16 µm; PFD group 134.39 ± 41.13 µm) between the restoration and the abutment under the unilateral screw-tightening condition ($P > 0.05$). Furthermore, when subjected to bilateral screw-tightening conditions, the marginal gaps between the restoration and the abutment were significantly reduced in all three groups (ZC group 37.33 ± 8.44 µm; ZFD group 37.14 ± 11.09 µm; PFD group 22.28 ± 10.45 µm). As shown in Table 2, there was no significant difference in passive fit between the ZC group (97.50 ± 20.36 µm) and ZFD group (64.72 ± 38.16 µm) ($P > 0.05$).

A significant difference ($P = 0.003$) was found in the passive fit condition between the restorations fabricated from the two materials and the abutments (Table 3). The marginal gap for PEKK was larger than that for zirconia under passive fit conditions; however, as shown in Table 4, under bilateral screw-tightening conditions (active fit), the marginal gap for the PFD group (22.28 ± 10.45 µm) was significantly smaller than that for the ZFD group (37.14 ± 11.09 µm) ($P = 0.015$).

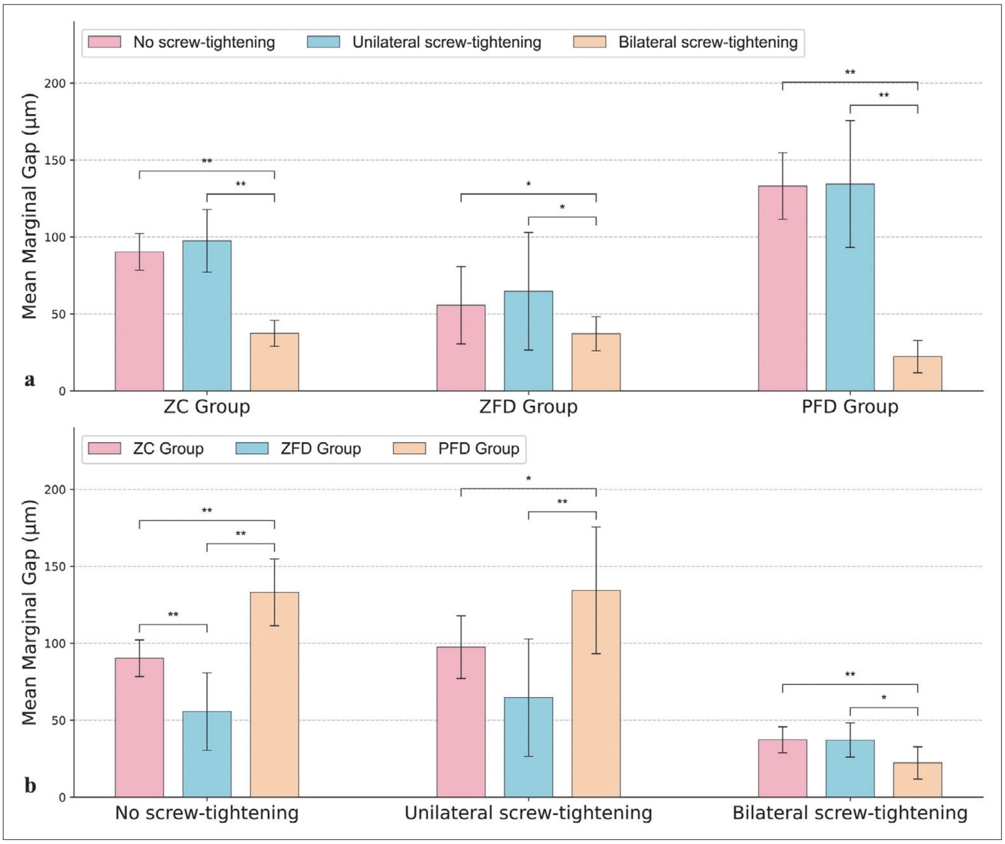

Fig 5a to b Marginal gaps for all three groups under different screw-tightening conditions. Gaps under different screw-tightening conditions within each group (a) and across groups under the same screw-tightening condition (b). *$P < 0.05$; **$P < 0.01$.

Table 2 Marginal gaps of three-unit ISFDPs under the unilateral screw-tightening condition using conventional and fully digital workflows.

Measurement location	ZC group, mean ± SD (μm)	ZFD group, mean ± SD (μm)	*P* value
Buccal	97.45 ± 21.25	64.24 ± 40.99	0.061
Lingual	97.55 ± 25.07	65.20 ± 41.00	0.082
Mean	97.50 ± 20.36	64.72 ± 38.16	0.051

Table 3 Marginal gaps of three-unit ISFDPs under the unilateral screw-tightening condition with different restoration materials.

Measurement location	ZFD group, mean ± SD (μm)	PFD group mean ± SD (μm)	*P* value
Buccal	64.24 ± 40.99	137.49 ± 50.14	0.006**
Lingual	65.20 ± 41.00	131.30 ± 34.99	0.004**
Mean	64.72 ± 38.16	134.39 ± 41.13	0.003**

**$P < 0.01$.

Table 4 Marginal gaps for three-unit ISFDPs under the bilateral screw-tightening condition with different restoration materials.

Measurement location	ZFD group, mean ± SD (μm)	PFD group, mean ± SD (μm)	*P* value
Buccal	41.00 ± 15.88	25.24 ± 12.05	0.042*
Lingual	33.28 ± 18.15	19.32 ± 09.48	0.081
Mean	37.14 ± 11.09	22.28 ± 10.45	0.015*

*$P < 0.05$.

No fractures or loosening of the implants, abutments or restorations were observed across all specimens during the 1,200,000 cycles of loading. As shown in Table 5, no significant differences were found in the mean of the marginal gaps of the restorations before and after cyclic loading among the three groups ($P > 0.05$).

Box plots were generated to visualise the loosening torque change (Fig 6). There was no significant dif-

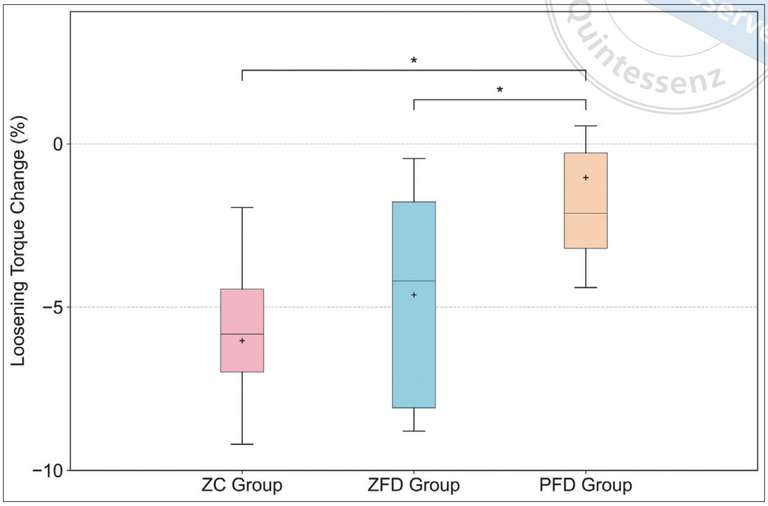

Fig 6 Loosening torque change for each group before and after cyclic loading. *$P < 0.05$.

Table 5 Repeated measures ANOVA of marginal gaps before and after cyclic loading. P value denotes the significance of marginal gap differences before and after cyclic loading.

Group	Before, mean ± SD (μm)	After, mean ± SD (μm)	*P* value
ZC group	32.46 ± 6.65	33.93 ± 6.59	0.180
ZFD group	34.50 ± 8.03	33.02 ± 11.23	0.789
PFD group	21.75 ± 5.72	20.68 ± 7.33	0.670
Main effect of time	0.686	NA	NA

NA, not applicable.

ference in loosening torque change between the ZC group (median −5.83%, Q_{25} −8.46%/Q_{75} −3.75%) and ZFD group (median −4.20%, Q_{25} −8.26%/Q_{75} −1.23%) ($P > 0.05$), whereas the PFD group (median −2.13%, Q_{25} −3.30%/Q_{75} 0.28%) exhibited significantly smaller loosening torque change compared to the former two groups ($P < 0.05$).

Discussion

This study demonstrates no significant difference in marginal fit and mechanical performance between restorations fabricated using conventional and fully digital workflows. Additionally, PEKK exhibits acceptable marginal fit and superior mechanical properties as a novel restorative material.

This study provides experimental data support for the clinical application of digital technology in fabricating three-unit ISFDPs. Compared with the model-based conventional workflow, the model-free, fully digital workflow mitigates the risk of deformation in conventional impressions and has fewer manual errors. Abduo et al[42] demonstrated that the digital impression offers greater accuracy than the conventional impression of the three-unit ISFDPs. This study further investigated the marginal fit and mechanical properties of multi-unit ISFDPs fabricated using different workflows, providing more intuitive data support for clinical applications.

In this study, no significant difference was found in marginal fit between the restoration and the abutment in the three-unit ISFDPs fabricated using the fully digital workflow compared to the conventional workflow. Under passive fit conditions, the marginal discrepancy was approximately 65 μm at the second molars, while under active fit conditions, it was within 40 μm. Stimmelmayr et al[12] utilised the silicone rubber impression replica technique to measure the marginal gaps between the restoration and the abutment of three-unit ISFDPs and suggested that a marginal discrepancy within 160 μm under the passive fit condition is acceptable. Similarly, Rutkunas et al[43] used a stereomicroscope to measure horizontal and vertical discrepancies between the restoration and the abutment and proposed that marginal discrepancies within 150 μm in both vertical and horizontal dimensions are acceptable. Therefore, the three-unit ISFDPs fabricated using the digital workflow in this study demonstrated excellent passive fit capabilities.

This study provides measurement results of marginal gaps before and after cyclic loading using high-precision 3D laser scanning microscopy, confirming no significant misfit in the three-unit ISFDPs fabricated with a fully digital workflow. The silicone replica technique is widely used to evaluate the marginal fit of restorations.[44] However, this technique also has limitations that lead to measurement errors, such as the tearing of fragile replicas. In this study, a 3D surface topography microscope with nanoscale resolution enabled precise marginal localisation and directly observed the marginal gaps. This method allowed for dynamic measurement of changes in the marginal gap before and after cyclic loading.

No complications were observed in all the three-unit ISFDPs fabricated by model-free fully digital workflows after 1,200,000 cycles of cyclic loading in this study. The authors found that the median loosening torque change of the PFD and ZFD groups was lower than that of the ZC group, with a significant difference observed between the PFD and ZC groups. The results indicate that the mechanical performance using the fully digital workflow is not inferior to that achieved with the conventional workflow. This result was consistent with those of Ramalho et al,[45] who compared the cyclic loading Weibull modulus of digital one-piece monolithic crowns and conventional crowns cemented onto titanium bases and found no significant difference.

The relationship between marginal misfit and loosening torque change is worth noting. This study found that the loosening torque change in the PFD group was significantly lower than that in the ZC group and the ZFD group. Before cyclic loading, the mean marginal gaps were 21.75, 32.46 and 34.50 µm in the PFD, ZC and ZFD group, respectively (Table 5). Under conditions of marginal misfit, tightening the restoration screws leads to additional stress. As cyclic loading progresses, thread slippage occurs, releasing stress and resulting in decreased loosening torque.[15] In summary, ISFDPs with larger marginal gaps exhibit a greater torque change rate after loading.

Computer numeric controlled (CNC) milling technology enables high-precision fabrication of ISFDPs. Commonly used materials for CNC-milled prostheses include titanium, zirconia and PEKK. Titanium is widely applied due to its excellent mechanical properties, biocompatibility and osseointegration capacity; however, its metallic colour may compromise aesthetics, and necessitates the use of a zirconia shell. A systematic review by Kim et al[46] reported a 5-year cumulative survival rate of 99.6% for zirconia-based ISFDPs. Regarding the precision of milling, Abduo et al[47] found that CNC-milled titanium and zirconia frameworks had comparable vertical marginal fit when used in three-unit ISFDPs.

This study suggests that PEKK can be used as a new restorative material, and its marginal fit and mechanical performance showed certain advantages. PEKK belongs to the polyaryletherketone family, similar to polyetheretherketone (PEEK). PEKK offers higher-performance thermoplastic properties than PEEK, excellent fracture resistance and a compression strength that exceeds PEEK by 80%.[48] Additionally, PEKK exhibits similar compressive strength and a smaller elastic modulus compared to dentine, indicating its potential as a restorative material.[32] The present authors found no significant difference in marginal fit before and after cyclic loading for PEKK, and the PFD group had the lowest loosening torque change among the three groups. Similarly, Alsadon et al[36] demonstrated that PEKK composite crowns exhibited the highest fatigue limit, excellent fatigue life and the highest survival rate under various loads.

A limitation of this study is that the findings are only applicable to a specific workflow under the OsseoSpeed TX Implant System involving three-unit ISFDPs with parallel implant axis. In model-free fully digital workflows, variations in implant axis angles and arch spans may affect the precision of restoration design. Therefore, further research is needed to evaluate the model-free fully digital workflow using various implant systems and implant axis angles.

Conclusion

In this study, the three-unit ISFDPs fabricated using a fully digital workflow showed non-inferior results in terms of marginal fit and mechanical performance compared to those fabricated using a conventional workflow. Notably, after simulating 5 years of cyclic loading, the three-unit ISFDPs fabricated using the fully digital workflow maintained excellent mechanical performance, with PEKK showing particularly superior properties that may enhance the long-term survival of the restorations. These results illustrate the clinical feasibility of utilising a fully digital workflow for the fabrication of three-unit ISFDPs and identify PEKK as a particularly promising material for CAD/CAM milling in restorative dentistry.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Dr Shi Qing SHI contributed to the experiment, data analysis and manuscript draft; Drs Dan Ni GUO and Mo

Di HENG contributed to the experiment, data collection and manuscript editing; Dr Bo CHEN contributed to the methodology and manuscript revision; Dr Shao Xia PAN contributed to the conceptualisation, supervision, funding support, project administration and manuscript editing and critical revision. All authors read and approved the final version of the manuscript.

(Received Mar 10, 2025; accepted Jun 15, 2025)

References

1. Guo D, Mühlemann S, Pan S, Zhou Y, Jung RE. A double-blind randomized within-subject study to evaluate clinical applicability of four digital workflows for the fabrication of posterior single implant crown. Clin Oral Implants Res 2023;34: 1319–1329.
2. Joda T, Brägger U. Digital vs. conventional implant prosthetic workflows: A cost/time analysis. Clin Oral Implants Res 2015;26:1430–1435.
3. Pan S, Guo D, Zhou Y, Jung RE, Hämmerle CHF, Mühlemann S. Time efficiency and quality of outcomes in a model-free digital workflow using digital impression immediately after implant placement: A double-blind self-controlled clinical trial. Clin Oral Implants Res 2019;30:617–626.
4. Mühlemann S, Kraus RD, Hämmerle CHF, Thoma DS. Is the use of digital technologies for the fabrication of implant-supported reconstructions more efficient and/or more effective than conventional techniques: A systematic review. Clin Oral Implants Res 2018;29:184–195.
5. Ma J, Zhang B, Song H, Wu D, Song T. Accuracy of digital implant impressions obtained using intraoral scanners: A systematic review and meta-analysis of in vivo studies. Int J Implant Dent 2023;9:48.
6. Hecker DM, Eckert SE. Cyclic loading of implant-supported prostheses: Changes in component fit over time. J Prosthet Dent 2003;89:346–351.
7. Ortega-Martínez J, Delgado LM, Ortiz-Hernández M, et al. In vitro assessment of PEEK and titanium implant abutments: Screw loosening and microleakage evaluations under dynamic mechanical testing. J Prosthet Dent 2022;127:470–476.
8. Ma M, Li X, Zou L, He J, Zhao B. Mechanical properties and marginal fit of prefabricated versus customized dental implant abutments: A comparative study. Clin Implant Dent Relat Res 2022;24:720–729.
9. Al-Meraikhi H, Yilmaz B, McGlumphy E, Brantley W, Johnston WM. In vitro fit of CAD-CAM complete arch screw-retained titanium and zirconia implant prostheses fabricated on 4 implants. J Prosthet Dent 2018;119:409–416.
10. Pan Y, Tsoi JKH, Lam WYH, Pow EHN. Implant framework misfit: A systematic review on assessment methods and clinical complications. Clin Implant Dent Relat Res 2021;23: 244–258.
11. Bhering CL, Marques Ida S, Takahashi JM, Barão VA, Consani RL, Mesquita MF. Fit and stability of screw-retained implant-supported frameworks under masticatory simulation: Influence of cylinder type: Stability of cast multiunit implant-supported frameworks. J Prosthodont 2016;25:459–465.
12. Stimmelmayr M, Groesser J, Beuer F, et al. Accuracy and mechanical performance of passivated and conventional fabricated 3-unit fixed dental prosthesis on multi-unit abutments. J Prosthodont Res 2017;61:403–411.
13. Katsoulis J, Takeichi T, Sol Gaviria A, Peter L, Katsoulis K. Misfit of implant prostheses and its impact on clinical outcomes. Definition, assessment and a systematic review of the literature. Eur J Oral Implantol 2017;10(suppl 1):121–138.
14. Zhang YJ, Qian SJ, Lai HC, Shi JY. Accuracy of photogrammetric imaging versus conventional impressions for complete arch implant-supported fixed dental prostheses: A comparative clinical study. J Prosthet Dent 2023;130:212–218.
15. Cibirka RM, Nelson SK, Lang BR, Rueggeberg FA. Examination of the implant-abutment interface after fatigue testing. J Prosthet Dent 2001;85:268–275.
16. El-Sheikh MAY, Mostafa TMN, El-Sheikh MM. Effect of different angulations and collar lengths of conical hybrid implant abutment on screw loosening after dynamic cyclic loading. Int J Implant Dent 2018;4:39.
17. Dorado S, Arias A, Jimenez-Octavio JR. Biomechanical modelling for tooth survival studies: Mechanical properties, loads and boundary conditions—A narrative review. Materials (Basel) 2022;15:7852.
18. Zupancic Cepic L, Frank M, Reisinger A, Pahr D, Zechner W, Schedle A. Biomechanical finite element analysis of short-implant-supported, 3-unit, fixed CAD/CAM prostheses in the posterior mandible. Int J Implant Dent 2022;8:8.
19. Joda T, Ferrari M, Brägger U. Monolithic implant-supported lithium disilicate (LS2) crowns in a complete digital workflow: A prospective clinical trial with a 2-year follow-up. Clin Implant Dent Relat Res 2017;19:505–511.
20. Joda T, Bragger U, Zitzmann NU. CAD/CAM implant crowns in a digital workflow: Five-year follow-up of a prospective clinical trial. Clin Implant Dent Relat Res 2019;21:169–174.
21. Abduo J, Elseyoufi M. Accuracy of intraoral scanners: A systematic review of influencing factors. Eur J Prosthodont Restor Dent 2018;26:101–121.
22. Ellakany P, Aly NM, Al-Harbi F. A comparative study assessing the precision and trueness of digital and printed casts produced from several intraoral and extraoral scanners in full arch and short span (3-unit FPD) scanning: An in vitro study. J Prosthodont 2023:32:423–430.
23. Alsharbaty MHM, Alikhasi M, Zarrati S, Shamshiri AR. A clinical comparative study of 3-dimensional accuracy between digital and Ccnventional implant impression techniques. J Prosthodont 2019;28:e902–e908.
24. Alshawaf B, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Accuracy of printed casts generated from digital implant impressions versus stone casts from conventional implant impressions: A comparative in vitro study. Clin Oral Implants Res 2018;29:835–842.
25. Schepke U, Meijer HJ, Kerdijk W, Cune MS. Digital versus analog complete-arch impressions for single-unit premolar implant crowns: Operating time and patient preference. J Prosthet Dent 2015;114:403–406.e1.
26. Hashemi AM, Hashemi HM, Siadat H, Shamshiri A, Afrashtehfar KI, Alikhasi M. Fully digital versus conventional workflows for fabricating posterior three-unit implant-supported reconstructions: A prospective crossover clinical trial. Int J Environ Res Public Health 2022;19:11456.
27. Cevik P, Schimmel M, Yilmaz B. New generation CAD-CAM materials for implant-supported definitive frameworks fabricated by using subtractive technologies. Biomed Res Int 2022;2022:3074182.
28. Bömicke W, Rammelsberg P, Stober T, Schmitter M. Short-term prospective clinical evaluation of monolithic and partially veneered zirconia single crowns. J Esthet Restor Dent 2017;29:22–30.

29. Lestan NG, Özcan M, Kocjan A, Oblak Č. Clinical evaluation of monolithic zirconia multiunit posterior fixed dental prostheses. J Prosthet Dent 2022;128:1258-1264.
30. Leitão CIMB, Fernandes GVDO, Azevedo LPP, Araújo FM, Donato H, Correia ARM. Clinical performance of monolithic CAD/CAM tooth-supported zirconia restorations: systematic review and meta-analysis. J Prosthodont Res 2022;66:374-384.
31. Mazza LC, Lemos CAA, Pesqueira AA, Pellizzer EP. Survival and complications of monolithic ceramic for tooth-supported fixed dental prostheses: A systematic review and meta-analysis. J Prosthet Dent 2022;128:566–574.
32. Alqurashi H, Khurshid Z, Syed AUY, Rashid Habib S, Rokaya D, Zafar MS. Polyetherketoneketone (PEKK): An emerging biomaterial for oral implants and dental prostheses. J Adv Res 2020;28:87–95.
33. Bae SY, Park JY, Jeong ID, Kim HY, Kim JH, Kim WC. Three-dimensional analysis of marginal and internal fit of copings fabricated with polyetherketoneketone (PEKK) and zirconia. J Prosthodont Res 2017;61:106–112.
34. Park JY, Bae SY, Lee JJ, Kim JH, Kim HY, Kim WC. Evaluation of the marginal and internal gaps of three different dental prostheses: Comparison of the silicone replica technique and three-dimensional superimposition analysis. J Adv Prosthodont 2017;9:159–169.
35. Baran MC, Demirci F, Tuzlalı M. Comparison of marginal and internal adaptation of three-unit fixed dental prostheses made using CAD/CAM metal-free materials. Eur J Oral Sci 2022;130:e12901.
36. Alsadon O, Wood D, Patrick D, Pollington S. Fatigue behavior and damage modes of high performance poly-ether-ketone-ketone PEKK bilayered crowns. J Mech Behav Biomed Mater 2020;110:103957.
37. Steiner M, Mitsias ME, Ludwig K, Kern M. In vitro evaluation of a mechanical testing chewing simulator. Dent Mater 2009;25:494–499.
38. Kreissl ME, Gerds T, Muche R, Heydecke G, Strub JR. Technical complications of implant-supported fixed partial dentures in partially edentulous cases after an average observation period of 5 years. Clin Oral Implants Res 2007;18:720–726.
39. Pjetursson BE, Thoma D, Jung R, Zwahlen M, Zembic A. A systematic review of the survival and complication rates of implant-supported fixed dental prostheses (FDPs) after a mean observation period of at least 5 years. Clin Oral Implants Res 2012;23(suppl 6):22–38.
40. Duan Y, Griggs JA. Effect of loading frequency on cyclic fatigue lifetime of a standard-diameter implant with an internal abutment connection. Dent Mater 2018;34:1711–1716.
41. Berejuk HM, Shimizu RH, de Mattias Sartori IA, Valgas L, Tiossi R. Vertical microgap and passivity of fit of three-unit implant-supported frameworks fabricated using different techniques. Int J Oral Maxillofac Implants 2014;29:1064–1070.
42. Abduo J, Palamara JEA. Accuracy of digital impressions versus conventional impressions for 2 implants: An in vitro study evaluating the effect of implant angulation. Int J Implant Dent 2021;7:75.
43. Rutkunas V, Dirse J, Kules D, Simonaitis T. Misfit simulation on implant prostheses with different combinations of engaging and nonengaging titanium bases. Part 1: Stereomicroscopic assessment of the active and passive fit. J Prosthet Dent 2023;129:589–596.
44. Villias AA, Kourtis SG, Karkazis HC, Polyzois GL. In vitro validation of Digital Image Analysis Sequence (DIAS) for the assessment of the marginal fit of cement-retained implant-supported experimental crowns. Int J Implant Dent 2021;7:12.
45. Ramalho IS, Bergamo ETP, Witek L, Coelho PG, Lopes ACO, Bonfante EA. Implant-abutment fit influences the mechanical performance of single-crown prostheses. J Mech Behav Biomed Mater 2020;102:103506.
46. Kim W, Li XC, Bidra AS. Clinical outcomes of implant-supported monolithic zirconia crowns and fixed partial dentures: A systematic review. J Prosthodont 2023;32:102–107.
47. Abduo J, Lyons K, Waddell N, Bennani V, Swain M. A comparison of fit of CNC-milled titanium and zirconia frameworks to implants. Clin Implant Dent Relat Res 2012;14(suppl 1): e20–e29.
48. Fuhrmann G, Steiner M, Freitag-Wolf S, Kern M. Resin bonding to three types of polyaryletherketones (PAEKs)-Durability and influence of surface conditioning. Dent Mater 2014;30:357–363.