Accuracy of polyvinyl siloxane ether and other impression materials in full-arch implant rehabilitation with varying angulations: A comparative *in vitro* study

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This study evaluated the accuracy of digital and conventional impressions using different materials in fully edentulous jaws with implants at varying angulations. Two master models were fabricated: one with four parallel and another with four implants placed according to the all-on-4 protocol. Impressions were obtained using three materials—polyvinyl siloxane (PVS), polyether (PE), and polyvinyl siloxane ether (PVSE)—and a digital scanner (TRIOS 4). Conventional impressions were cast, scanned with an extraoral scanner, and compared with the reference models *via* Geomagic Control X software. In the parallel model, digital impressions exhibited significantly greater deviation values than PE (p=0.016). In the angulated model, PE demonstrated significantly lower deviation values compared to PVSE (p=0.007) and digital impressions (p=0.016). Deviation values increased with implant angulation in all groups, except PVSE, which showed no statistically significant difference. Polyether provided the highest accuracy. Implant angulation adversely affected accuracy across most impression methods.

Keywords: Impression accuracy, Polyvinyl siloxane ether, Polyether, Polyvinylsiloxane

INTRODUCTION

Achieving a biologically, mechanically, and esthetically successful implant-supported prosthesis requires highly accurate impressions. The long-term success of implant therapy is closely linked to the precision of the prosthetic fit, which must facilitate effective oral hygiene and ensure passive adaptation in order to prevent biological and mechanical complications[1,2].

Two primary workflows are employed for capturing impressions in complete-arch implant rehabilitation: conventional and digital techniques. In the conventional approach, elastomeric impression materials are used in conjunction with impression copings to accurately record the three-dimensional position of implants and surrounding soft tissues[3]. In the digital workflow, scan bodies are attached to the implants, and impressions are acquired using intraoral scanners to generate a virtual model[4].

To enhance impression accuracy, various elastomeric materials have been introduced. Among these, polyether (PE) and polyvinyl siloxane (PVS) are commonly preferred due to their excellent dimensional stability and high precision. A more recent hybrid material, polyvinyl siloxane ether (PVSE), combines the hydrophilic properties and rigidity of PE with the elastic recovery characteristics of PVS[5,6]. Despite increasing interest in full-arch implant-supported prostheses, obtaining highly accurate impressions in such cases remains a considerable clinical challenge[7]. Anatomical complexity, implant angulation, and extended scanning spans elevate the risk of distortion or stitching errors, particularly in complete-arch rehabilitations. Therefore, the selection of an optimal impression technique is critical to achieving clinical success in these demanding scenarios[8,9].

Recent studies have increasingly focused on improving accuracy in full-arch implant impressions[10,11], particularly in light of the growing adoption of digital workflows and the development of novel elastomeric materials such as PVSE. Chemically, PVSE features a modified siloxane backbone with ether-based side chains, which are designed to enhance flowability while preserving dimensional stability. Despite its promising properties, limited data are available on the clinical performance of PVSE in implant-supported restorations, especially in comparison with digital impression techniques. Clinical relevance of this issue lies in achieving passive fit, which is essential to prevent biomechanical complications; even minor dimensional inaccuracies in impressions can compromise the long-term success of full-arch prostheses[2].

Digital workflows offer several advantages over conventional techniques, including reduced chairside time, improved patient comfort, and streamlined digital communication with dental laboratories[12,13]. Once a digital scan is acquired, computer-aided design (CAD) software enables virtual planning and fabrication of prostheses. Although digital impressions are gaining popularity, particularly for complete arch restorations, concerns persist regarding their accuracy. Several studies have suggested that digital techniques can provide comparable or even superior accuracy to conventional elastomeric impressions, especially in short-span or partially edentulous cases where scanning conditions are more favourable[10,14-16]. However, other research have shown that in full-arch implant scenarios, digital scans may result in clinically unacceptable deviations due to accumulated stitching errors, extended scan spans, and reduced anatomical landmarks[11,17,18].

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These discrepancies tend to increase with greater implant angulation and inter-implant distance[8,17]. As a result, the reliability of digital impressions in full-arch rehabilitations remains a topic of ongoing debate.

The present study addresses this critical gap, as no comprehensive evaluations have directly compared PVSE with digital techniques in full-arch, angulated implant settings, where the risk of inaccuracy is greatest[19]. By targeting this clinically relevant scenario, the study aims to provide new insights into the performance of both conventional and emerging impression materials.

To evaluate impression accuracy, three-dimensional comparisons between the reference and test model can be conducted using reverse engineering software. This process involves superimposing the STL files and calculating deviations along the x, y, and z axes through vector analysis[9,20,21]. According to the Revised American Dental Association Specification No. 19 for elastomeric impression materials, deviations within ±20 μm are considered ideal for precision-demanding restorations, such as single unit crowns, while deviations up to ±150 μm are generally accepted as clinically acceptable in most restorative cases[22]. However, it is important to note that these standards were originally intended for single or short-span restorations rather than full arch-implant supported prostheses. Nevertheless, due to the absence of universally established criteria for full-arch restorations, many recent studies have adopted the the ±150 μm threshold as a benchmark for clinical acceptability in such scenarios[23,24].

Although numerous studies have investigated the accuracy of impressions in full-arch implant restorations, evidence regarding the performance of PVSE remains limited[6,19,25-28]. Therefore, the aim of this study was to compare the accuracy of conventional impression techniques using PVS, PE, PVSE, and digital method in implant models with both parallel and angulated configurations. The first null hypothesis was that there would be no significant difference in the accuracy of impressions between the impression techniques and materials. The second null hypothesis was that there would be no significant difference in the accuracy of impressions between the parallel and angulated implant configurations.

MATERIALS AND METHODS

This study was designed as an *in vitro* investigation evaluating the accuracy of dental impression materials and techniques. As it did not involve human participants or animal subjects, ethical approval was not required. All materials utilized were standard, commercially available dental products, and no clinical or biological data were collected or analyzed[29].

For the production of the reference models, two standard edentulous maxillary models made of polyurethane were used (Edudent, Istanbul, Turkey). Polyurethane was selected due to its mechanical properties, including a modulus of elasticity and comprehensive strength comparable to those of human cortical bone, making it suitable for implant placement and standardized *in vitro* testing[30-32].

Bone-level implants with a cylindrical-conical hybrid body, and an internal hex connection (Mode Medikal, Istanbul, Turkey) were used in both models. The implants were fabricated from Grade IV titanium (ASTM F 67), and measured 4.1 mm in diameter and 10 mm in length.

In the reference model of Group 1, four parallel implants were inserted in the canine and first molar regions. All implants were positioned perpendicular to the occlusal plane, and their angulations were considered to be 0°.

In the reference model of Group 2, four implants were also placed in the canine and first molar regions. The anterior implants were parallel to each other and oriented perpendicular to the occlusal plane, with 0° angulation. The posterior implants, however, were positioned at a distal angulation of 30° relative to the vertical axis, simulating the clinical conditions consistent with the All-on-4 technique.

A parallelometer was used to determine the correct angulations during implant placement. All implants were placed in accordance with the manufacturer's guidelines.

Additionally, two reference implants were embedded in the midline of the palate of both models to facilitate accurate superimposition of the reference and scanned models. One reference implant was positioned near the incisive foramen, and the other was placed posterior to the most distal implants in the molar region.

Two different multi-unit abutment configurations were used depending on the implant model. In the parallel implant model, straight multi-unit abutments (0°, 2.5 mm height) were placed on both anterior and posterior implants. In the angulated implant model, straight multi-unit abutments (0°, 2.5 mm height) were used for the anterior implants, whereas angled multi-unit abutments (30°, 3.5 mm height) were placed on the posterior tilted implants to harmonize emergence profiles and maintain visual alignment across all sites.

All abutments were fabricated from titanium alloy (Ti-6Al-4V ELI, ASTM F136), featured internal hex connections, and were torqued to 25 Ncm in accordance with the manufacturer's protocol (Mode Medikal). These multi-unit abutments enabled standardized abutment-level impressing taking, and ensured consistent positioning of the impression copings.

A power analysis was conducted using the G*power software to determine the appropriate sample size based on root mean aquare (RMS) error measurements. The effect size (d) was calculated as 0.1292. With a statistical power of 0.80, and a significance level of α=0.05, the minimum required sample size per group was found to be n=4. However, to enhance reliability and robustness of the results, the sample size was increased to 10 per group.

To obtain the three-dimensional images of the reference models, four straight multi-unit abutments were placed on the reference model of Group 1, and torqued to 25 Ncm in accordance with the manufacturer's instructions. Multi-unit scan bodies were then attached using light finger pressure (5–10 Ncm) according to the manufacturer's recommendations. For Group 2, two straight multi-unit abutments were placed on the anterior implants, and two angled multi-unit abutments were placed in the posterior implants, all torqued with 25 Ncm torque following the manufacturer's protocols. The positions and angulations of the abutments were verified using a parallelometer.

To enhance scan accuracy, both reference models were sprayed with an anti-reflection spray (Beta Proses BT-37, Tekirdağ, Turkey) to eliminate surface glare. The models were scanned using a 3Shape 1E Laboratory Scanner, which has demonstrated a RMS error of 14.3±0.3 µm for full-arch scans[33]. The resulting scans were saved as STL files for further analysis.

The digital impressions were obtained using a TRIOS 4 intraoral scanner (3Shape, Copenhagen, Denmark), connected to a an external computer running the manufacturer's proprietary software. All scans were performed by a single experienced operator to ensure standardization. Each reference model was scanned ten times, as determined by the power analysis. The scanning protocol was followed strictly in accordance with the Trios user instructions[34]. Occlusal surfaces were scanned first, starting from the right maxillary tuberosity and progressing across the edentulous ridge toward the left maxillary tuberosity, passing over the scan bodies. After completing the occlusal scan, the scanner tip was rotated to the buccal side at a 45° angle, and the vestibular surfaces were scanned in the same direction. Then, the scanner was rotated to the palatal side at the same angle, and scanning was repeated from right hamular notch to the left, completing the full arch. Each scan was reviewed, and artifacts were removed. Missing areas were rescanned. Final STL files were exported and transferred *via* USB device.

For the conventional impression procedures, the scan bodies on both reference models were removed, to allow for elastomeric impressions. On each reference model, four multi-unit impression copings were placed and hand-tightened with light finger pressure (5–10 Ncm) in accordance with the manufacturer's instructions. For all impression materials, direct splinted technique was used. A total of 10 impressions were taken per material, resulting in 30 impressions for each reference model.

A prefabricated resin bar was used to splint the impression copings. The distance between the copings was measured with a caliper, and the bar was cut accordingly. Each segment was then attached to the copings using cold acrylic resin (Pattern Resin LS, GC, Leuven, Belgium) (Fig. 1). The resin was prepared in an incremental manner, and allowed to set at room temperature for 3 min, following the manufacturer's instructions. This procedure was repeated seperately for each impression material.

To ensure consistent tray positioning, stock open trays with window spaces corresponding to the implant sites were selected to match the size of the models. The

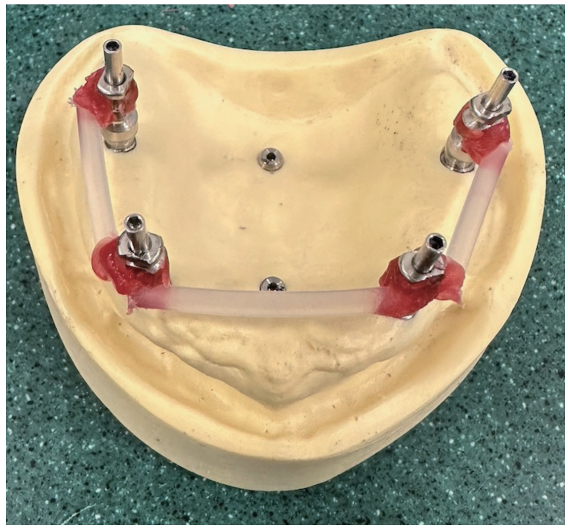

Fig. 1　Impression copings splinted using prefabricated resin bars and cold acrylic resin.

anatomical corners of the polyurethane models extended beyond the tray borders, providing physical landmarks to guide consistent tray seating. This design also inherently limited the seating pressure applied by finger force, thereby reducing the variability in impression material thickness around the copings.

All impressions were made by a single operator with over 20 years of experience in prosthodontics, under standardized environmental conditions (25°C, 50% relative humidity). An auto-mixing device (Pentamix 2, 3M ESPE, Seefeld, Germany) and Garant dispenser gun were used to eliminate mixing inconsistencies and air entrapment in the putty material. During the setting period, bilateral finger pressure was applied to standardize seating load across all impresions.

After setting, the impression copings were carefully unscrewed, and the tray was removed from the model in an anterosuperior direction. Implant replicas were subsequently attached to the copings according to the manufacturer's recommendations.

For impressions with PVS; fast-set Hydroise Heavy Body and Hydroise Light Body (Zhermack, Badia Polesine, Italy) materials were used. Prior to each impression, DMG tray adhesive for A-silicones (DMG, Hamburg, Germany) was applied to the tray surfaces and allowed to dry for 3 min, in accordance with the manufacturer's instructions. The mixed heavy-body material was loaded into the tray, and the light body material was dispensed directly onto the heavy-body using a dispenser gun to obtain a one-step impression. The setting time was 4 min, as specified by the manufacturer.

For the PE imprssions, a soft monophase polyether material (3M Impregum Penta Soft, Germany) was used. Prior to each impression, 3M polyether adhesive (3M) was applied to the impression trays and allowed to dry for 15 min, in accordance with the manufacturer's instructions. The setting time for the material was 3 min and 15 s, as specified by the manufacturer.

For the PVSE impressions, a medium-bodied PVSE material (Identium, Kettenbach, Eschenburg, Germany) was used. Identium adhesive was applied to each impression tray and allowed to dry for 5 min, in accordance with the manufacturer's instructions. The material was allowed to set for 4 min and 30 s, as per the manufacturer's guidelines.

Before pouring the casts, all impressions were inspected to confirm the absence of discrepancies, air bubbles, loosened impression copings, incomplete polymerization, or other defects. Double-mixing method was used to minimize the dimensional changes of the stone. Type IV dental stone (Angel Dent, Istanbul, Turkey) was used, prepared by mixing 100 g of powder with 20 mL of distilled water, in accordance with the manufacturer's recommendations. The mixture was vacuum-mixed using a Smartmix unit (Amann-Girrbach, Pforzheim, Germany). As instructed by the manufacturer, a setting time of 120 min was allowed before detaching the impressions the casts. Screws were carefully loosened to remove the impressions. All cast-pouring procedures were performed by the same experienced operator. Prior to scanning, the casts were stored at room temperature for 24 h to ensure complete setting and moisture stabilization.

For comparative measurements, appropriate multi-unit abutments and scan bodies were placed on the dental stone models containing embedded implant replicas, enabling digital scanning using a laboratory scanner (3Shape 1E Lab Scanner). The same type of multi-unit abutments used in the reference models were first attached to the replicas to facilitate accurate scan body positioning and to ensure proper alignment with the reference datasets. The positions and angulations of the abutments were verified by using a parallelometer. Prior to scanning, all models were coated with an anti-reflection spray (Beta Proses BT-37 Spray) to eliminate surface glare and enhance scan precision. Scanning was conducted in accordance with the 3Shape user instructions. Following each scan, the acquired surfaces were throughly examined for any artifacts or errors. All scan data were exported as standard tesselation language (STL) files for further analysis.

The digital data obtained from both the intraoral scanner and the laboratory scanner were imported into Geomagic Control X software (Geomagic, Morrisville, NC, USA) for three-dimensional analysis. The reference and test models were aligned using a combination of initial alignment and best-fit registration functions within the software, with alignment guided by preregistered reference points and implant positions. Following alignment, the 3D Deviation Color Map tool was utilized to visualize surface deviations between the models (Figs. 2 and 3). Root Mean Square error values were calculated to quantify the deviation between the scanned impression models and the corresponding reference models. Twelve comparison points were selected per model, located around the implant sites and along the edentulous ridge crest-areas critical for hybrid prosthesis adaptation. The basal portion of the models, visible in the scan but clinically irrelevant, was excluded from the RMS analysis to prevent skewing the

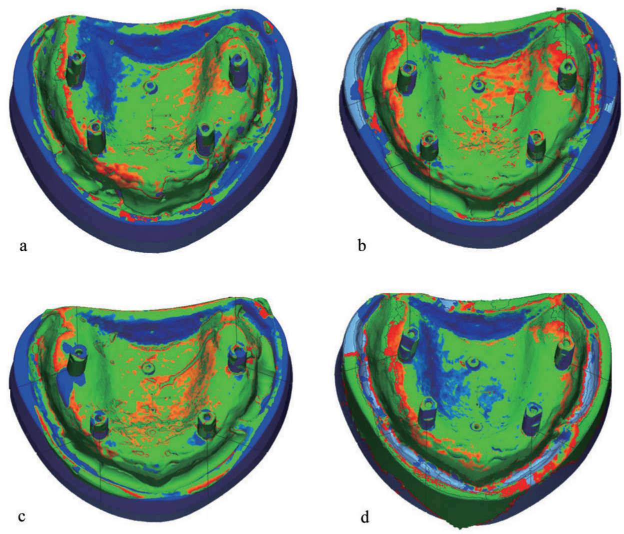

Fig. 2 Color-coded three-dimensional deviation maps of angulated model impressions obtained using Geomagic Control X: (a) PVS, (b) PE, (c) PVSE, (d) Digital.
The color scale indicates the magnitude of deviation: blue represents negative deviation (scanned surface below reference), green indicates no deviation, and red represents positive deviation (scanned surface above reference).

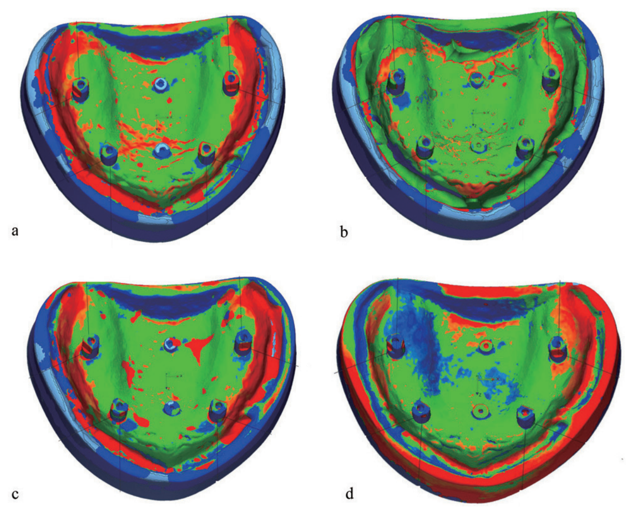

Fig. 3 Color-coded three-dimensional deviation maps of parallel model impressions obtained using Geomagic Control X: (a) PVS, (b) PE, (c) PVSE, (d) Digital.
The color scale indicates the magnitude of deviation: blue represents negative deviation (scanned surface below reference), green indicates no deviation, and red represents positive deviation (scanned surface above reference).

results. Only clinically pertinent anatomical regions were included in the accuracy evaluation.

The methodology was reviewed by an independent statistician. Statistical analyses were performed using IBM SPSS Statistics 22 program (IBM, Armonk, NY, USA). The normality of the data distribution was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests, confirming that all parameters were normally distributed. A two-way analysis of variance (ANOVA) was conducted to evaluate the effect of the impression technique and implant angulation on deviation values. *Post hoc* comparisons were performed using Tukey's test. Statistical significance was set at $p<0.05$.

RESULTS

Descriptive properties of the groups are presented in Table 1. The distribution of all groups was considered normal, as the skewness and kurtosis values fell within the acceptable range of +1.5 and −1.5. Skewness describes the asymetry of the data distribution, while kurtosis reflects the weight of the tails in comparison to a normal distribution. Accordingly, parametric tests were deemed appropriate for statistical comparisons.

There was a statistically significant difference in deviation values between the two model groups ($p=0.001$; $p<0.05$), indicating that implant angulation significantly affected impression accuracy. Similarly, a statistically significant difference was found among the different impression materials ($p=0.001$; $p<0.05$), suggesting that the material type influenced the accuracy of the impressions. However, the combined effect of model and impression groups on the deviation amount was not statistically significant ($p=0.502$; $p>0.05$), indicating that implant angulation and impression material did not have a combined effect on deviation values (Table 2).

Within the PVS group, the deviation value for the angulated model was statistically significantly higher than that of the parallel model ($p=0.003$; $p<0.05$). Similarly, in the PE group, the angulated model exhibited statistically significantly greater deviation compared to the parallel model ($p=0.003$; $p<0.05$). In contrast, no statistically significant difference was observed between the parallel and angulated models in the PVSE group ($p=0.171$; $p>0.05$). In the digital impression group, the angulated model showed statistically significantly higher deviation than the parallel model ($p=0.001$; $p<0.05$) (Table 3 and Fig. 4).

In the parallel model group, a statistically significant difference in deviation values was observed among the impression groups ($p=0.001$; $p<0.05$). *Post hoc* analysis revealed that the PVSE group exhibited statistically significantly greater deviation than the PVS group ($p=0.001$), PE group ($p=0.001$), and digital impression group ($p=0.019$) ($p<0.05$). The deviation value in the digital impression group was also statistically significantly higher than that of the PE group ($p=0.016$; $p<0.05$). No other statistically significant differences were found among the remaining groups ($p>0.05$) (Table 3 and Fig. 4).

In the angulated model group, a statistically significant difference in deviation values was observed among the impression groups ($p=0.003$; $p<0.05$). According to the *post hoc* analysis, the PE group demonstrated statistically significantly lower deviation compared to the PVSE group ($p=0.007$) and the digital

Table 1 Descriptive data of the groups

Groups		*n*	Mean	x̄±Sd	Se	Min	Max	Median	Kurtosis	Skewness
PVS	Parallel	10	0.0073	0.005	0.002	0.002	0.015	0,008	−1.302	0.264
	Angulated	10	0.0157	0.006	0.002	0,002	0.023	0.017	1.055	−1.357
PE	Parallel	10	0.0064	0.003	0.001	0.000	0.011	0.006	−0.373	−0.492
	Angulated	10	0.0120	0.004	0.001	0.005	0.017	0.012	−0.61	−0.491
PVSE	Parallel	10	0.0175	0.005	0.002	0.011	0.024	0.016	−1.031	0.065
	Angulated	10	0.0223	0.009	0.003	0.008	0.035	0.025	−1.354	−0.205
Digital	Parallel	10	0.0120	0.001	0.000	0.010	0.014	0.013	−1.298	−0.177
	Angulated	10	0.0213	0.006	0.002	0.009	0.026	0.024	1.043	−1.429

Table 2 Evaluation of the impact of model and impression material groups on accuracy

	Type III sum of squares	df	Mean square	F	*p*
Model groups (parallel/angulated)	0.001	1	0.001	33.456	0.001*
Impression material groups	0.001	3	0.001	16.053	0.001*
Model groups * impression groups	0.0001	3	0.00002	0.792	0.502

Two-way ANOVA test *$p<0.05$

Table 3 Evaluation of the accuracy of model and impression groups

Impression groups	Parallel model	Angulated model	p
	Mean±(SD)	Mean±(SD)	
Polyvinylsiloxane	0.0073±0.005^{Aac}	0.0157±0.006^{Bab}	0.003*
Polyether	0.0064±0.003^{Aa}	0.0120±0.004^{Bb}	0.003*
Polyvinyl siloxane ether	0.0175±0.005^{Ab}	0.0223±0.009^{Aa}	0.171
Digital	0.0120±0.001^{Ac}	0.0213±0.006^{Ba}	0.001*
p	0.001*	0.003*	—

Two-way ANOVA test *$p<0.05$
The different lowercase letters in the columns indicate differences among impression groups.
The different uppercase letters in the rows indicate differences among parallel and angulated model groups within each impression material.

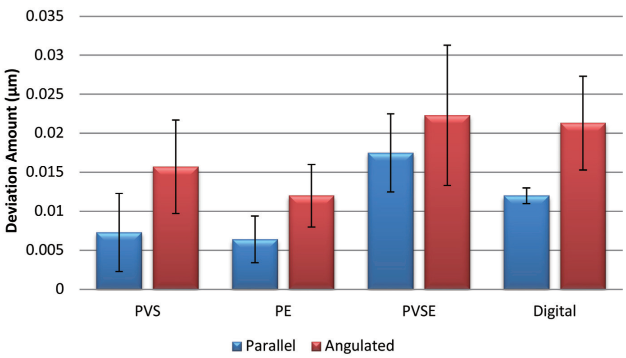

Fig. 4 Comparison of the impact of model and impression groups on accuracy measured by using RMS values.

impression group (p=0.016) (p<0.05). No other statistically significant differences were found among the remaining groups (p>0.05) (Table 3 and Fig. 4).

DISCUSSION

The findings of this study resulted in the rejection of both null hypotheses. Statistically significant differences were identified among the impression techniques, including conventional methods using PVS, PE, and PVSE, as well as the digital impression group (p=0.001; p<0.05). Furthermore, implant angulation was found to have a significant effect on impression accuracy (p=0.001; p<0.05).

In PVS, PE, and digital groups, the deviation observed in the angulated implant model was significantly higher than in the parallel implant model (p=0.003 for PVS and PE, p=0.001 for digital). In contrast, although the PVSE group also demonstrated an increase in deviation with implant angulation, the difference was not statistically significant (p=0.171; p>0.05). This finding may indicate that PVSE is less sensitive to implant angulation; however, its overall performance remained inferior compared to the other materials. The increased deviation observed in the conventional groups may be attributed to distortion of the impression material during tray removal, especially in angulated implant scenarios where undercuts are more pronounced[35]. In the digital group, the higher deviation noted in the angulated model could be related to increased inter-scan body distance in full-arch situations, which may exacerbate image stitching errors—a known limitation of intraoral scanning[10,11,17]. Unlike conventional methods, digital impressions are not subject to material deformation; however, scanning accuracy tends to decrease as the span and geometric complexity of the arch increases[36,37]. To fully comprehend the impact of implant angulation on digital impression accuracy, further clinical studies are warranted, as digital methods are not influenced by material distortion.

Several studies in the literature have compared the accuracy of digital impressions in parallel and angulated implant cases. Consistent with the present study, many have reported that implant angulation negatively affects the accuracy of digital impressions[36,37]. Conversely, other investigations have found no significant impact of implant angulation on impression accuracy[35,38,39]. These conflicting findings may be attributed to variations in study methodologies, implant configurations, and the use of different intraoral scanners.

When comparing implant angulation groups, PVSE demonstrated significantly greater deviation than PVS (p=0.001), PE (p=0.001), and digital impressions (p=0.019) in the parallel model. Additionally, the deviation observed in the digital impression group was significantly higher than that of the PE group (p=0.016; p<0.05). In the angulated model, digital impressions exhibited significantly greater deviation compared to PE (p=0.016), while PE demonstrated significantly less deviation than both PVSE (p=0.007) and digital impressions (p=0.016). Among all tested materials, PE yielded the highest accuracy in both implant configurations. This superior performance can be attributed to PE's high rigidity and extensive cross-linking due to the presence of imine groups in its polymer chain, which likely reduces rotational discrepancies during impression removal[28,40]. Conversely, the inferior performance of PVSE may be related to its limited elastic recovery, potentially compromising dimensional stability during tray removal[25]. The reduced accuracy observed in the digital group may be partially explained by the study design, as full-arch impressions involving four implants with varying angulations may have led to cumulative scanning errors. Prior studies have shown that as the span and inter-implant distances increase, intraoral scanning accuracy diminishes, particularly at the terminal points of the arch, contributing to overall deviation[38].

The findings of this study are consistent with previous research on conventional impression materials[19,25,28,40]. As reported in earlier studies, PE yielded the most accurate outcomes among elastomeric materials[19,28]. However, some studies have found no statistically significant differences in accuracy between PVS and PE impressions[41-45]. Implant angulation is another critical factor influencing impression accuracy, with numerous studies having explored its varying impact on conventional materials[46-51]. In this study, two distinct models—parallel and angulated implant configurations—were employed to replicate relevant clinical scenarios. PVSE, a relatively recent addition to the family of elastomeric impression materials, has been proposed for use in the impression of implant-supported restorations[26]. However, there is currently limited number of studies in the literature about PVSE to reach a conclusion about its accuracy outcomes[6,19,25-28]. This study sought to adress this gap by assessing PVSE's performance in both parallel and angulated full-arch implant models. The results demonstrated that PVSE exhibited lower accuracy compared to PE, PVS, and digital impressions, corroborating previous findings[19,25,28]. Importantly, this study is among the first to directly compare PVSE with digital techniques in a full-arch, angulated implant context, offering new insights into its clinical limitations.

A systematic review by Guo *et al.*[40] evaluated the accuracy of impression materials for implant-supported fixed complete dentures, with particular focus on PE and PVS. The review concluded that both materials generally demonstrated comparable accuracy. However, PE outperformed PVS in scenarios involving implants angled beyond 15 degrees. The findings of the present study, particularly in the angulated model group, are in agreement with this conclusion, further supporting the superior performance of PE in cases with increased implant angulation.

Kurtulmuş-Yılmaz *et al.*[19] evaluated the impression accuracy of PVS, PE, and PVSE in both parallel and angulated implant models, reporting that implant angulation increased deviations for all tested materials. Consistent with the current study, PVSE exhibited the highest deviation in both implant configurations. However, in contrast to the current findings, no statistically significant difference was observed between PE and PVS in their study. This discrepancy may be attributed to differences in experimental design; as their study employed a partially edentulous model. In such scenarios, the inherent flexibility of PVS may offer an advantage by facilitating impression removal with less distortion.

In the study conducted by Vojdani *et al.*[27], the accuracy of PVS, PE, and PVSE was evaluated in both parallel and nonparallel implant configurations. Their results indicated that in parallel implant cases, the type of material did not significantly influence accuracy. However, in angulated implant scenarios, PVS demonstrated significantly greater accuracy than both PE and PVSE. These findings differ from those of the present study. This difference may stem from methodological differences, as Vojdani *et al.* employed partially dentate maxillary models. In such cases, anatomical undercuts are more pronounced, and the higher modulus of elasticity of PVS may provide an advantage during impression removal.

This study has several limitations. First, as an *in vitro* study, it did not replicate intraoral conditions such as saliva, soft tissue behavior, or patient movement. Second, only one brand per impression material and scanner was tested, limiting the generalizability of the findings. Third, implant placement was restricted to four internal connection implants with a maximum angulation of 30°, which may not represent all clinical scenarios. Fourth, CAD alignment and prosthesis fabrication were not evaluated, and only abutment-level impressions were used, making comparisons with studies using implant-level impressions more difficult. Fifth, the impressions techniques differed between groups: scan bodies were not splinted in the digital group, whereas conventional groups used splinted impression copings. Additionally, in the conventional impression groups, a segmented prefabricated resin bar was used to simulate splinting instead of a one-piece 360-degree metal or resin framework, which may affect the clinical applicability of the findings. This discrepancy may have influenced the accuracy results and limits the direct comparison between the two techniques. Additionally, current clinical digital workflows, particularly for full-arch impressions, often incorporate methods such as double scanning or verification jigs, which were not included in the present study. Lastly, a high-precision extraoral scanner was used as the reference, but using a coordinate measuring machine (CMM) might have yielded more precise baseline data.

CONCLUSION

Within the limitations of this *in vitro* study, the findings indicate that both the impression material and implant angulation significantly influence the accuracy of complete arch implant impressions. Implant angulation was found to negatively affect impression accuracy, resulting in greater deviations compared to parallel configurations. Among the evaluated materials, PE yielded the highest accuracy in both parallel and angulated implant models. Although PVSE was developed to combine the advantages of PE and PVS, it exhibited inferior performance in both configurations. Digital impressions demonstrated lower accuracy than those obtained with PE in both parallel and angulated complete-arch models. All test groups exhibited deviation values within clinically acceptable limits.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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