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Original article

# Evaluation of hypermobile teeth deviation during impression taking in a partially edentulous dental arch: An *in vitro* study comparing digital and conventional impression techniques

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**Abstract**

**Purpose:** This study aimed to compare the deviation of hypermobile teeth in partially edentulous dental arches during impression taking using digital and conventional techniques.

**Methods:** A partially edentulous mandibular model with three target hypermobile teeth (including the left first premolar, #34; left second molar, #37; and right first premolar, #44), was used as the simulation model. After reference data were acquired using a desktop scanner, impressions of the simulation model were obtained using a digital intraoral scanner (IOS) and two conventional techniques (hydrocolloid material with a stock tray and silicone material with a custom tray as impression data (n=12/group). The three-dimensional accuracy (root mean square value) and two-dimensional accuracy (mesiodistal and buccolingual displacements) of the target teeth in each impression dataset were calculated based on the reference data. The comparison among three impression techniques was statistically performed using the Kruskal–Wallis test (α=0.05).

**Results:** For #34 and #44, the three- and two-dimensional accuracies of the impressions fabricated through data acquired through digital scanning (digital impression) were significantly superior to those of the hydrocolloid impression ($P < 0.05$), whereas no significant difference was found between the digital and silicone impressions. For #37, no significant difference in the accuracy of the impression data for the target teeth was observed among the three impression techniques.

**Conclusions:** Digital impression acquiring using an IOS is recommended over using a conventional hydrocolloid impression to prevent the deviation of hypermobile teeth in partially edentulous dental arches. Hypermobile tooth deviation in digital impression data depends on the tooth location.

**Keywords:** Digital impression, Hypermobile tooth, Intraoral scanner, Removable partial denture, Tooth mobility

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## 1. Introduction

An abutment tooth of a removable partial denture (RPD) is at higher risk of tooth loss than a non-abutment tooth[1]. Some previous studies have reported that hypermobile RPD abutment teeth exhibit a poor survival rate after denture placement[2], whereas others have reported successful outcomes with proper design and fabrication of RPDs[3]. Passivity of the retainer is required to prevent the transmission of adverse forces from the retainer to the abutment tooth[4]. However, impression pressure can cause hypermobile RPD abutment teeth to be displaced during conventional impression taking using physical impression materials[5], resulting in a lack of retainer passivity.

***WHAT IS ALREADY KNOWN ABOUT THE TOPIC?***

*» Digital impressions obtained using intraoral scanners (IOSs) are widely used in removable partial denture treatment. Although the contactless IOS system is assumed to be advantageous for obtaining accurate impressions of partially edentulous dental arches that include hypermobile teeth, no previous study has evaluated contactless scanning.*

***WHAT THIS STUDY ADDS?***

*» Our study highlights that using a digital impression technique better prevents displacement of hypermobile teeth in a partially edentulous dental arch than using a conventional hydrocolloid impression technique. Digital impression techniques are challenged with improving the accuracy for hypermobile teeth that are isolated.*

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Recently, the impressions fabricated through data acquired through digital scanning (digital impressions) obtained using intraoral scanners (IOSs) have been widely used for fabricating RPDs[6]. Digital impressions are expected to provide accurate impressions of partially edentulous dental arches that include hypermobile teeth, without causing tooth deviation, because the system is contactless. Digital impressions have been reported to produce proper RPD fitting, especially for Kennedy Class III or IV cases with small mucosal areas[7,8]. Meanwhile, a digital impression was reported to show superior trueness and inferior precision compared with conventional impressions[9].

Despite their advantages, digital impressions obtained using IOSs are affected by specific factors that reduce impression accuracy, such as large areas of mucosa[10], tooth isolation via the mucosal area[11], and tooth location far from the scan origin[12]. Previous studies have assessed differences in impression accuracy among various impression techniques by comparing their gaps with reference data impressions representing the real morphology of dental arches[9–12]. This method enables the assessment of whether a digital impression obtained using an IOS is effective in capturing the proper morphology of partially edentulous dental arches, including hypermobile teeth. However, no study has investigated the accuracy of digital impressions of partially edentulous dental arches that include hypermobile teeth.

In this *in vitro* study, we aimed to compare the deviation of target teeth with hypermobility in the acquired impression data between digital and conventional impression techniques. The null hypothesis was that there would be no significant difference in the deviation of the target hypermobile teeth between the two techniques.

## 2. Materials and Methods

### *2.1. Simulation model fabrication*

A mandibular Kennedy Class II, Modification 1, partially edentulous model (NISSIN DENTAL MODEL E50-528; Nissin Dental Products Inc., Kyoto, Japan) with four missing teeth (left second premolar, #35; left first molar, #36; right first molar, #46; and right second molar, #47) and three target teeth (left first premolar, #34; left second molar, #37; and right first premolar, #44) was used as the master model. As components of the master model, the artificial teeth, including the target teeth, were made of melamine resin, whereas the residual ridge was made of epoxy resin. The master model and the three target teeth were selected based on previous studies[11,12]. Among the target teeth, #34 and #37 were adjacent to the mucosal area and served as the RPD abutments, whereas #44 had adjacent teeth in both the mesial and distal areas. Tooth #37 was surrounded by mucosal areas and isolated from the remaining teeth.

After placing 5 mm-diameter steel spheres at the midpoint of the mucosal area on the left side and at the retromolar pad on the right side as references for data assessment (**Fig. 1A**), an impression mold of the master model was made using silicone impression material (DUPLICONE; Shofu Inc., Kyoto, Japan). The root of each target tooth was wrapped with 1 mm-thick paraffin wax and placed into the impression mold (**Fig. 1B**) before the high-strength dental stone (NEW FUJIROCK; GC Corporation, Tokyo, Japan) was poured. After the stone cast, including the artificial teeth of the targets, was completed, the paraffin wax was washed away and replaced with a silicone material (EXAMIXFINE regular type; GC Corporation) to provide a 1 mm-thick artificial periodontal ligament (**Fig. 1C and 1D**). The tooth mobility of the target teeth was then adjusted using an electronic tooth mobility measuring device (Periotest M®; Medizintechnik Gulden, Modautal, Germany) by shortening the height of the artificial periodontal ligament toward the root apex in the same manner as described in previous studies[13,14]. Periotest M® consists of a handpiece containing a metal slug that accelerates toward the tooth surface and taps it 16 times in 4 seconds. The results of tapping are calculated as Periotest values (PTVs), which range from −8 (very little mobility) to 50 (very large mobility). With the adjustment of the artificial tooth mobility at PTVs of 20.0 to 29.9 (equivalent to clinical class II tooth mobility[15]), the stone cast including the target hypermobile teeth was completed as the simulation model. Twelve simulation models were developed using the aforementioned methods. A sample size of 12 in each group was determined based on a previous study that evaluated the displacement of hypermobile teeth during conventional impression procedures[5].

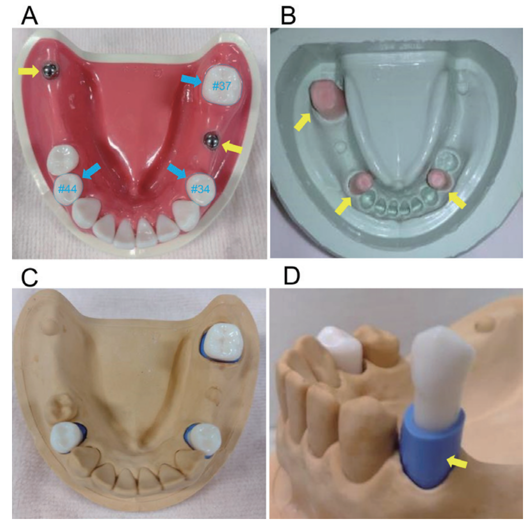


**Fig. 1.** Master and simulation models. A: Master model; the blue arrows indicate the target hypermobile teeth and yellow arrows indicate the reference steel spheres, B: impression mold with placement of artificial teeth wrapped with 1 mm-thick paraffin wax (yellow arrows), C: completed simulation model, and D: artificial periodontal ligament (yellow arrow).

### *2.2. Reference data acquisition*

**Figure 2** shows the flowchart of the experimental procedures used in this study. First, digital data of each simulation model were acquired through digital scanning using a desktop scanner (EDGE; DOF Inc., Seoul, Republic of Korea) with a manufacturer's reported accuracy of 7 μm (ISO 12836)[16] and saved in a standard triangulated language (STL) file format as reference data (Ref. data #1 in **Fig. 2**) to evaluate the deviation of the target teeth. Reference data obtained during this phase were used to evaluate the accuracy of the digital and hydrocolloid impressions.

### *2.3. Digital impression data acquisition*

A digital impression for each simulation model was captured by full-arch scanning using an IOS (TRIOS 3; 3Shape, Copenhagen, Denmark) and software (TRIOS version 20.1.10.1; 3Shape). The data acquired were saved in STL file format as digital impression data.

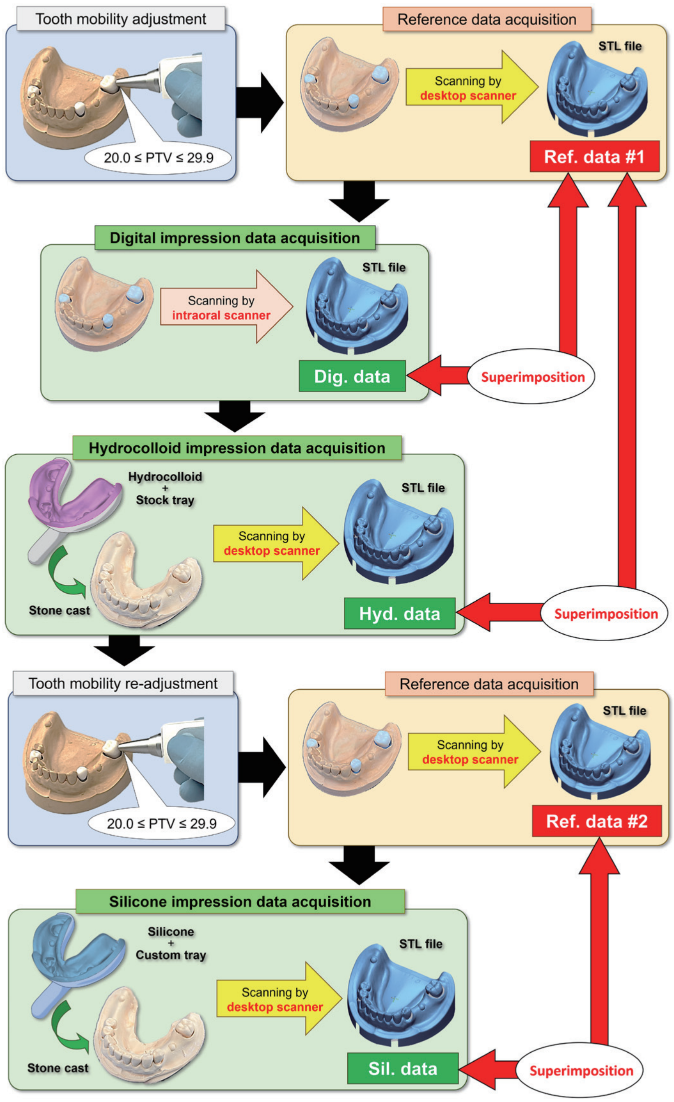


**Fig. 2.** Overall flowchart of the experimental procedures. STL: standard triangulated language, IOS: intraoral scanner, PTV: Periotest value, Ref. data: reference data, Dig. data: digital impression data, Hyd. data: hydrocolloid impression data, Sil. data: silicone impression data.

Based on a previous study[17], scanning was initiated from #37 to the retromolar pad on the right side over the occlusal surfaces of the posterior teeth in straight motion and the incisal edges of the anterior teeth in zigzag motion, followed by scanning of the buccal (labial) lingual surfaces (**Fig. 3**). The digital data obtained were saved in STL file format. All scans were performed by an experienced operator (K.S.). Before data acquisition, the operator was calibrated to maintain the number of images from 2600 to 2800 for each scanning and to obtain a data precision of 20 μm among 10 scans.

*2.4. Conventional impression data acquisition*

After digital impression data acquisition, conventional impressions were obtained for each simulation model using the following two types of impression materials: 1) hydrocolloid (alginate) (AROMA FINE PLUS; GC Corporation) and 2) silicone (medium body) (EXAHIFLEX Regular Type, GC Corporation).

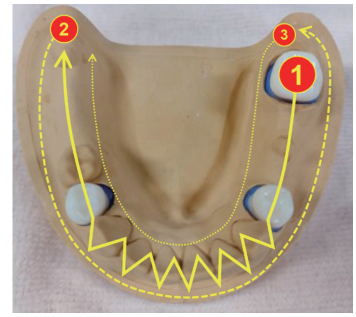


**Fig. 3.** Scanning strategies used in this study. Scanning was initiated from #37 to the retromolar pad on the right side over the occlusal surfaces of posterior teeth in a straight motion and the incisal edges of anterior teeth in a zigzag motion (1), followed by scanning of the buccal (labial) (2) and lingual surfaces (3).

First, a conventional impression was taken using a hydrocolloid impression material incorporated into a stock tray (SANKIN IMPRESSION TRAY; Dentsply Sirona K.K., Tokyo, Japan) for each simulation model, and the dental cast was fabricated using high-strength dental stone (NEW FUJIROCK; GC Corporation). Then, using a desktop scanner, the digital data of the model was acquired in STL file format as hydrocolloid impression data.

Using the dental model, after acquiring the hydrocolloid impression data, a custom tray was fabricated using an autopolymerizing tray resin (OSTRON II, GC Corporation) with a 1.4 mm-thick relief on the remaining teeth. With hydrocolloid impression taking, the target hypermobile teeth are slightly depressed owing to the physiological contact between the hydrocolloid impression material and target teeth, whereas no such depression is observed with digital impression taking owing to the contactless system of the IOS. Therefore, readjustment of the mobility of the target teeth and reacquisition of the reference data were required before taking silicone impressions (**Fig. 2**). To readjust the mobility of the target teeth in the simulation model, the artificial periodontal ligaments of the target teeth were replaced with new ones that were adjusted to PTVs ranging from 20.0 to 29.9. Subsequently, digital scanning was performed using a desktop scanner to obtain the reference data (Ref. data #2 in **Fig. 2**) to evaluate the silicone impression. After adjusting the tooth mobility and acquiring the reference data, a conventional impression was made using a silicone impression material incorporated into a custom tray, and a dental cast was fabricated using high-strength dental stone. The digital data of the model was acquired in STL file format as silicone impression data using a desktop scanner.

All conventional impressions were obtained by an experienced operator (M.K.). Regarding the direction of impression tray insertion, the distal border of the tray was initially placed on the posterior edge of the simulation model and the tray was rotated such that the direction of the impression pressure on the remaining teeth was approximately perpendicular to the occlusal plane. Before the impression was taken, the operator was calibrated to standardize the amount of impression material used and the tray insertion procedure.

*2.5. Three-dimensional accuracy (RMS value)*

According to previous studies, the root mean square (RMS) value, in μm, of the deviations at all STL structural points included in each

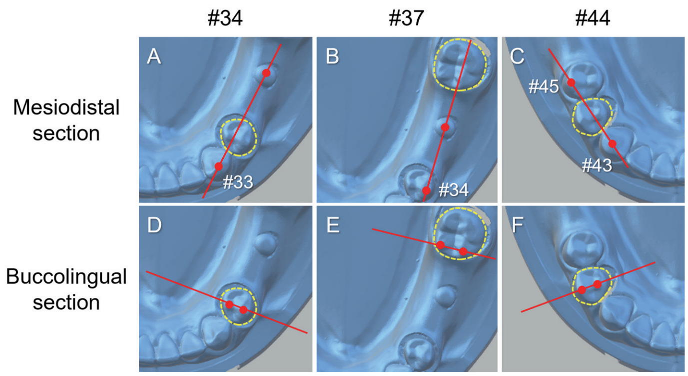


**Fig. 4.** Reference points for definition of mesiodistal and buccolingual sections. The mesiodistal sections (A: #34, B: #37, and C: #44) and buccolingual sections (D: #34, B: #37, and F: #44) represented by red lines were defined by the reference points (red points) including cusp tops and center coordinates of steel spheres.

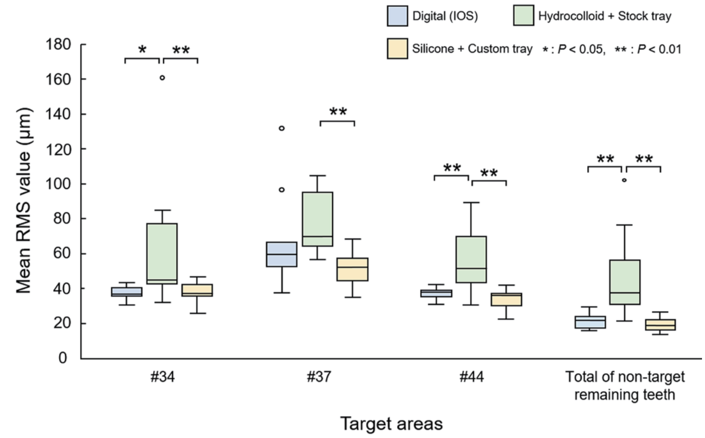


**Fig. 5.** Box plots of three-dimensional accuracy represented as root mean square values in μm for all standard triangulated language structural points including target areas (each target hypermobile tooth and all the remaining nontarget teeth). IOS: intraoral scanner, RMS: root mean square.

target tooth was calculated based on the reference data to represent three-dimensional accuracy of the data for each impression[11,12]. Using three-dimensional inspection software (GEOMAGIC CONTROL X; 3D Systems, Inc., Rock Hill, SC, USA), each impression data point was superimposed onto the reference data using the best-fit method[18]. Based on structural points on the surfaces of the remaining teeth, excluding the target hypermobile teeth, each impression data point was located at a position that precisely matched the reference data. Subsequently, the impression and reference data were superimposed, and the following evaluation target areas were trimmed: 1) #34, 2) #37, 3) #44, and 4) all remaining teeth except the target hypermobile teeth. Each trimming step was performed along with the area outline on the reference data. After area trimming, the RMS values were calculated for each target hypermobile tooth and all the remaining teeth, excluding the target hypermobile teeth. Positive deviations (yellow to red) represented the external positions relative to the reference data, whereas negative deviations (light green to blue) represented the internal positions.

### *2.6. Two-dimensional accuracy (mesiodistal and buccolingual displacements)*

In addition to three-dimensional accuracy, two-dimensional accuracy of the target hypermobile teeth was assessed. Using the three-dimensional inspection software, the maximum distances (largest deviations including positive and negative values; μm) between the impression and reference data on both the mesiodistal and buccolingual cross-sections (i.e., the mesiodistal and buccolingual accuracies, respectively) were calculated as the representative values of two-dimensional accuracy. To standardize the mesiodistal and buccolingual sections, the occlusal plane was defined as the plane that included the left and right canine cusps and the top of the steel sphere placed on the right retromolar pad, ensuring that it was vertical to the mesiodistal and buccolingual sections. The mesiodistal and buccolingual sections of the target hypermobile teeth were defined to include the two reference points in the reference data shown in **Figure 4**. Notably, the vertical displacement of target hypermobile teeth was not assessed because the mobility of the target teeth was set to be equivalent to clinical class II tooth mobility (PTVs of 20.0 to 29.9), indicating that these teeth would not be depressible[19].

### *2.7. Statistical analysis*

The Kolmogorov–Smirnov test confirmed that the acquired data did not show normality. Therefore, the Kruskal–Wallis test was used to perform statistical comparisons of the three- and two-dimensional accuracies among the three impression techniques (digital, hydrocolloid, and silicone). Pairwise comparisons were performed using the Mann–Whitney U test and Bonferroni correction. All statistical analyses were performed using statistical software (SPSS version 28.0; IBM Corp., Armonk, NY, USA), with the significance level set at 0.05.

## 3. Results

### *3.1. Three-dimensional accuracy*

The results of the three-dimensional accuracy evaluations (RMS values of deviations at all STL structural points included in the target areas) for each target tooth and the remaining nontarget teeth are shown in **Figure 5**. The digital impression revealed median RMS values (interquartile range [IQR]) of 36.1 (4.2), 58.9 (11.5), and 38.1 (3.6) μm for #34, #37, and #44, respectively. The silicone impression revealed median RMS values of 36.5 (5.6), 51.8 (10.8), and 36.0 (6.3) μm for #34, #37, and #44, respectively. No significant differences were observed between the digital and silicone impressions. The median RMS values for the hydrocolloid impression were 44.2 (30.4), 69.0 (22.2), and 51.1 (22.6) μm for #34, #37, and #44, respectively. In contrast to the silicone impression, the hydrocolloid impression revealed significantly inferior three-dimensional accuracy than the digital impression for #34 ($P = 0.021$) and #44 ($P = 0.007$), whereas no significant difference in three-dimensional accuracy was found for #37. Additionally, the three-dimensional accuracy of the hydrocolloid impression was significantly lower than that of the silicone impression for #34 ($P = 0.004$), #37 ($P = 0.001$), and #44 ($P < 0.001$).

Regarding the nontarget teeth, the median RMS values (IQR) obtained with the digital, hydrocolloid, and silicone impression techniques were 21.9 (6.85), 37.8 (20.9), and 19.1 (5.7) μm, respectively. The hydrocolloid impression revealed significantly inferior three-dimensional accuracy than the digital ($P = 0.002$) and silicone ($P <$

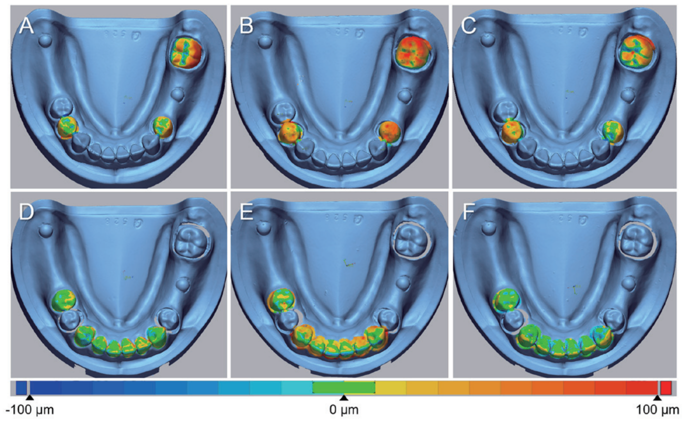


**Fig. 6.** Typical color mapping images showing deviations of the target hypermobile teeth (including A: digital, B: hydrocolloid, and C: silicone impression techniques) and the remaining nontarget teeth (including D: digital, E: hydrocolloid, and F: silicone impression techniques). The color bar indicates the deviation calculated based on the reference data. Positive deviations represent the external position relative to the reference (yellow to red), whereas negative deviations represent the internal position (light green to blue).

0.001) impressions, whereas no significant difference was observed between the digital and silicone impressions.

Typical color mapping images indicating deviations from the reference data are shown in **Figure 6**. Color mapping of the target hypermobile teeth showed visibly greater deviations with the hydrocolloid impression (**Fig. 6B and 6E**) than with the digital (**Fig. 6A and 6D**) and silicone (**Fig. 6C and 6F**) impressions.

*3.2. Two-dimensional accuracy*

The results of the two-dimensional accuracy assessments (maximum distances between the impression and reference data) in the mesiodistal section are shown in **Figure 7A**. The median values (IQR) for #37 were 129.5 (66.7), 175.5 (49.9), and 125.2 (27.5) µm, whereas those for #44 were 62.8 (14.3), 81.9 (41.8), and 64.8 (15.4) µm with the digital, hydrocolloid, and silicone impressions, respectively. No significant differences in the mesiodistal accuracies for #37 and #44 were observed among the three impression techniques. The values for #34 were 57.4 (17.0), 82.2 (78.8), and 66.0 (26.1) µm with the digital, hydrocolloid, and silicone impressions, respectively. The digital impression revealed a significantly superior mesiodistal accuracy for #34 than the hydrocolloid impression did ($P = 0.022$).

The results of two-dimensional accuracy evaluation in the buccolingual section are shown in **Figure 7B**. The median values (IQR) for #34 were 71.5 (20.9), 90.0 (26.7), and 71.9 (25.4) µm, whereas those for #44 were 69.4 (15.9), 73.1 (42.0), and 64.5 (15.4) µm with the digital, hydrocolloid, and silicone impressions, respectively. No significant differences in the buccolingual accuracies for #34 and #44 were observed among the three impression techniques. However, the results for #37 were 137.5 (34.1), 142.3 (51.4), and 96.9 (64.8) µm with the digital, hydrocolloid, and silicone impression techniques, respectively. The digital impression revealed significantly greater buccolingual accuracy for #37 than the hydrocolloid impression did ($P = 0.028$).

Among the three target hypermobile teeth, #37 showed a visible difference in the direction of deviation (i.e., tooth displacement) between the three impression techniques (**Fig. 8**). In the mesiodistal direction, both conventional impressions (namely, hydrocolloid and silicone) exhibited tooth displacement in the distal direction, whereas the digital impressions demonstrated various directions and degrees of tooth displacement. For the buccolingual direction, the digital impression exhibited tooth displacement in the buccal direction, whereas the silicone impression demonstrated tooth displacement in the lingual direction. Hydrocolloid impressions exhibited various directions and degrees of tooth displacement.

## 4. Discussion

To the best of our knowledge, this is the first study to investigate the effectiveness of digital systems for taking impressions in partially edentulous dental arches that have hypermobile teeth. Using a mandibular Kennedy Class II, Modification 1, partially edentulous model, we compared the displacement of three target hypermobile teeth based on the tooth position in the reference data acquired using a desktop scanner across digital, hydrocolloid, and silicone impression techniques. Overall, the digital impression showed significantly smaller deviations in the hypermobile teeth than the hydrocolloid impression. Therefore, the null hypothesis was rejected. However, no significant difference in target tooth deviation was observed between the digital and silicone impression techniques.

In general, the results were consistent for the three- and two-dimensional accuracies, indicating that the hydrocolloid impression had the lowest accuracy, whereas the accuracies of the digital and silicone impressions were comparable. Regarding the digital impression, the three-dimensional accuracy of #37 was greater than that of the other target teeth (#34 and #44), which was consistent with the results of previous studies using the same experimental model and target teeth[11,12]. Sakamoto *et al.* suggested that the inferior accuracy of #37 could be due to it being isolated from the remaining teeth via a mucosal area, resulting in a lack of landmarks for data stitching[11]. Previous studies have demonstrated that placing an artificial landmark on, for example, the mucosal area, may improve the data accuracy of the mucosal area[20] and isolated tooth[21], suggesting that steel spheres can be used as artificial landmarks and could be helpful in obtaining improved data accuracy for #37, as observed in this study. Moreover, the accuracy of the digital impression data may be affected by the morphology of the mucosal areas, location of the remaining teeth, and size of the remaining dental arch.

A previous study indicated that the refractive indices of the scanned objects may critically affect the accuracy of the data acquired using IOSs[22]. In this *in vitro* study, artificial teeth made of melamine were used as target objects. We measured the refractive index of the melamine teeth, determining it to be 1.49, whereas that of natural teeth (enamel) is 1.63[23]. Therefore, the difference between the refractive indices of natural and artificial teeth did not critically affect the accuracy of the digital impression data. However, the difference between denture-bearing mucosa and dental stones may limit the reliability of the numerical data in clinical situations. Analytical comparisons were performed using data acquired from a simulation model fabricated with the same materials (i.e., high-strength dental stone and artificial melamine teeth), assuming that our findings based on the data comparison would be meaningful. Notably, ambient light illumination has a considerable influence on the accuracy of the data acquired using IOSs[24]. Thus, standardizing the simulation factors of light and shadow using an ambient light-measuring instrument and a typodont incorporated into a

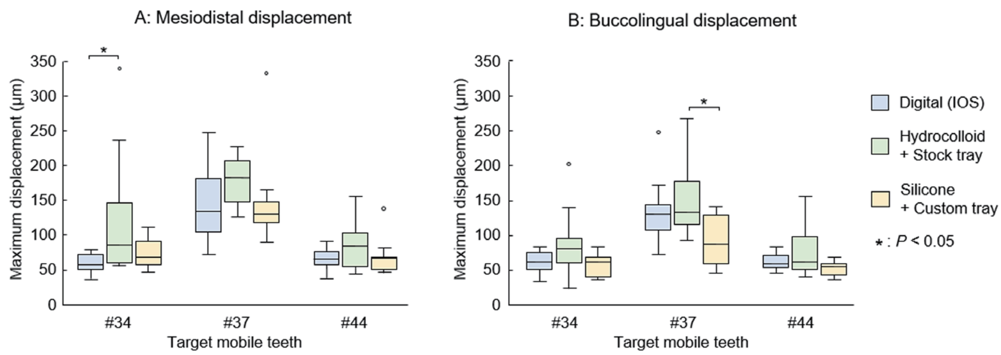


**Fig. 7.** Box plots of two-dimensional accuracy represented as maximum distances from the reference data on the mesiodistal and buccolingual sections (A and B, respectively) of each target hypermobile tooth. Note that the two-dimensional accuracy was statistically assessed in absolute values. IOS: intraoral scanner.

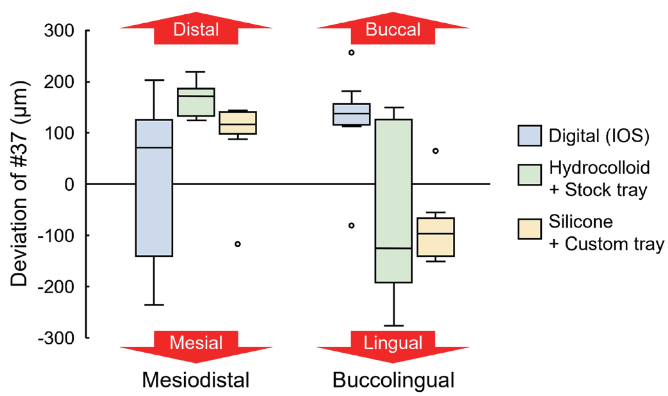


**Fig. 8.** Box plots of the deviation (tooth displacement) of #37 on the mesiodistal and buccolingual sections. Note that the positive values on mesiodistal and buccolingual sections reveal tooth displacement toward distal and lingual directions, respectively. IOS: intraoral scanner.

mannequin simulator could be helpful. However, due to the lack of standardization of ambient light illumination, our findings based on digital impressions were limited to experimental situations.

Several studies have reported that the more posterior the target tooth is, the greater the deviation in the buccal direction[11,25]. These findings agree with our findings on buccolingual two-dimensional accuracy using the digital impression (**Fig. 8**). In contrast, for mesiodistal accuracy, the digital impression revealed various signed values for the deviation of #37, ranging from –236.6 to +202.4 μm. Previous studies have indicated that a mucosal area mesially facing the remaining tooth may result in poorer data accuracy[26] and mesial displacement of the tooth[11]. These issues, which specifically affect the accuracy of digital impression data, may help explain the widely distributed deviation of #37. To assess the effect of digital impressions on differently positioned RPD abutments, the target teeth included abutments with adjacent teeth in both the mesial and distal areas [#44], facing a modification space [#34], and with the most posteriorly located abutment isolated from the remaining teeth by a mucosal area [#37]. Only one pattern of partially edentulous dental arches was evaluated in this study, which limits the generalizability of our findings, especially to the maxillary arches. Moreover, we used a mandibular simulation model without a maxillary model as the opposite object, which may have facilitated the acquisition of digital impressions without any contact between the IOS and remaining teeth. Pressure from the IOS can depress the teeth upon contact, especially in the case of hypermobile teeth. Therefore, in clinical practice, clinicians should ask patients to open their mouths maximally and avoid touching hypermobile teeth with the IOS.

Regarding conventional impression techniques, several factors can contribute to the deviation of hypermobile teeth during impression taking, including fluidity and curing characteristics of the impression material, approaching speed of the impression tray toward the remaining dentition, amount of impression material, and design of the impression tray[5,27,28]. According to the manufacturer's instructions, the consistency of medium-body elastomeric impression material (ISO 4823) used in this study is 37 mm[29], whereas that of the hydrocolloid impression material is unknown. Therefore, the effect of material consistency on hypermobile tooth displacement cannot be discussed in relation to our findings. Prosthodontists generally use hydrocolloid impression materials with various water to powder ratios, depending on the mucosal condition of patients who are edentulous, to facilitate border molding[30]. This suggests that the consistency of the impression materials can affect the displacement of impression objects. Additionally, the location of the spillway and spacer thickness between the remaining teeth and a custom tray can render the influence of the choice of impression material unclear[5]. Custom trays are clinically used to record the proper shape of both the remaining teeth and the mucosal area because they provide sufficient clearance for impression materials and can be trimmed or border molded to acquire the desired shape[31]. In this study, the spacer thickness was standardized to 1.4 mm and custom trays were fabricated without any spillways. This might have led to a higher impression pressure than that exhibited by the stock trays, as well as standardized pressure on every surface of the remaining teeth, resulting in a smaller tooth deviation observed with the silicone impression using a custom tray. In particular, #37 was originally tilted in the lingual direction, as is typically observed in actual oral cavities. The direction of the impression pressure was perpendicular to the occlusal plane; therefore, the conventional impression techniques tended to push #37 in the lingual direction, as shown in **Figure 8**. When using a stock tray for the mandibular dentition, the impression pressure escapes in the distal direction[5,32], which may explain the distal displacement found in the hydrocolloid impression. The selection of which physical impression material, namely, hydrocolloid or silicone, to use critically affects the reproducibility of detail[33], suggesting that the difference between the hydrocolloid and silicone impressions found in this study was mainly related to the types of impression trays. As shown in **Figure 6E**, the hydrocolloid impression led to greater tooth deviations, even in the remaining nontarget (i.e., immobile) teeth. It has been suggested that the inferior reproducibility of detail of hydrocolloid impression materials[33] may cause potential deviations, regardless of tooth mobility, and lower the impression accuracy for hypermobile teeth. Adding the following two groups to our targets would have been helpful in clarifying the independent effect of each impression material and tray type: 1) a hydrocolloid impression using a custom tray and 2) a silicone impression using a stock tray. However, such combinations of impression materials and trays are not commonly used in clinical practice. Therefore, these groups were excluded from this study. Additionally, the calibration of the operators taking impressions was not strictly performed, especially for conventional impression taking. This may have resulted in a significant deviation in the impression data.

The American Dental Association (ADA) accepts a dimensional change of 0.5% or less 24 hours after recording an impression using conventional materials[34]. In this study, the diameters of the target artificial teeth were approximately 7.0 mm for #34 and #44, and 12.0 mm for #37, indicating that the three-dimensional accuracy, as shown in **Figure 5**, was comparable to the dimensional changes of 0.5% with the digital and silicone impressions; conversely, the hydrocolloid impression resulted in a dimensional change outside the ADA's acceptance range. Therefore, our findings indicate that digital and silicone impressions may be clinically acceptable for obtaining impressions of partially edentulous dental arches with hypermobile teeth. In this study, the mobility of the target teeth was standardized at a PTV ranging from 20 to 29, representing a mobility of less than 1 mm in the buccolingual direction (Class 2 of the Miller classification) [19,35]. The accuracy of digital impression techniques does not affect the degree of tooth mobility because digital systems are contactless, whereas the accuracy of conventional impression techniques declines critically with increasing tooth mobility. Additionally, the standardized thickness of the artificial periodontal ligament (1.0 mm) may help minimize tooth deviation under standardized impression pressure with a silicone impression using a custom tray. Clinically, hypermobile teeth with weakened periodontal tissue require blockouts of deep undercut areas, such as expanded embrasures, and are at high risk of being extracted when an impression tray with cured impression material is removed. However, digital impressions are free of these issues. Overall, the difference in tooth deviation between digital and silicone impressions was unclear. However, silicone impression materials are not always recommended as the first choice because of their rigidity. Therefore, it is conceivable that digital impressions can be more broadly used clinically than silicone impressions for taking impressions of partially edentulous dental arches, including those with remaining hypermobile teeth.

This study had several limitations. First, for RPD fabrication, the remaining teeth and mucosal areas should be recorded when taking the impression. However, this study did not consider the accuracy of recording the mucosal area. Mucosal compression was not simulated because impression materials can generate such compression, whereas IOSs cannot. A previous *in vivo* study reported a significant difference in the impression accuracy of mucosal areas between the digital and silicone impression techniques[36]. Further clinical studies are required to assess the effectiveness of digital impressions on the clinical outcomes of RPDs fabricated for partially edentulous dental arches with hypermobile teeth. Second, this study was performed only in a mandibular Kennedy Class II, Modification 1, partially edentulous model, and the target hypermobile teeth were limited to the premolars and molars. A previous study assessing hypermobile mandibular incisors suggested that the anatomical morphology of a hypermobile tooth affects the direction of displacement during the taking of impressions[28]. It remains unclear how effective a digital impression is when used for other conditions of partially edentulous dental arches. Third, post hoc tests revealed that the power of the statistical analyses was insufficient for some datasets, such as the two-dimensional accuracy in the mesiodistal section, indicating the risk of a type II error. Finally, this *in vitro* study did not consider factors that could clinically affect impression accuracy, such as the direction of impression pressure, amount of saliva, and mucosal characteristics. Therefore, further clinical studies are required to investigate the effects of these factors on impression accuracy.

## 5. Conclusions

Within the limitations of this study, the use of a digital impression acquired using an IOS is recommended over that of a conventional hydrocolloid impression with a stock tray to prevent hypermobile tooth deviation when taking impressions of partially edentulous dental arches. Moreover, the degree of deviation of hypermobile teeth depends on the location of the tooth in the partially edentulous dental arch. It remains unclear whether digital impressions are effective, especially for hypermobile teeth isolated from the remaining teeth by mucosal areas. Further studies are required to deepen our understanding of this phenomenon.

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## Conflict of interest statement

The authors declare that there is no conflict of interest.

## References

[1] Miyamoto T, Morgano SM, Kumagai T, Jones JA, Nunn ME. Treatment history of teeth in relation to the longevity of the teeth and their restorations: outcomes of teeth treated and maintained for 15 years. J Prosthet Dent. 2007;97:150–6. https://doi.org/10.1016/j.prosdent.2007.01.007, PMID:17394913

[2] Kern M, Wagner B. Periodontal findings in patients 10 years after insertion of removable partial dentures. J Oral Rehabil. 2001;28:991–7. https://doi.org/10.1111/j.1365-2842.2001.00788.x, PMID:11722713

[3] Watanabe C, Wada J, Mizutani K, Nagayama T, Uchida H, Shibata Y, *et al.* Radiographic predictive factors for 10-year survival of removable partial denture abutment teeth: alveolar bone level and density. J Prosthodont Res. 2022;67:437–43. https://doi.org/10.2186/jpr.JPR_D_22_00034, PMID:36418082

[4] Phoenix RD, Cagna DR, DeFreest CF. Stewart's clinical removable partial prosthodontics. 4th ed. Chicago: Quintessence Publishing Co; 2008, p. 71-4.

[5] Nishi Y, Hamano T, Kawahata N, Nagaoka E. Displacement of a mobile tooth during impression procedure: effect of impression tray design. J Oral Rehabil. 1998;25:553–9. https://doi.org/10.1046/j.1365-2842.1998.00280.x, PMID:9722103

[6] Fueki K, Inamochi Y, Wada J, Arai Y, Takaichi A, Murakami N, *et al.* A systematic review of digital removable partial dentures. Part I: clinical evidence, digital impression, and maxillomandibular relationship record. J Prosthodont Res. 2022;66:40–52. https://doi.org/10.2186/jpr.JPR_D_20_00116, PMID:33504721

[7] Kattadiyil MT, Mursic Z, AlRumaih H, Goodacre CJ. Intraoral scanning of hard and soft tissues for partial removable dental prosthesis fabrication. J Prosthet Dent. 2014;112:444–8. https://doi.org/10.1016/j.prosdent.2014.03.022, PMID:24882595

[8] Mansour M, Sanchez E, Machado C. The use of digital impressions to fabricate tooth-supported partial removable dental prostheses: a clinical report. J Prosthodont. 2016;25:495–7. https://doi.org/10.1111/jopr.12346, PMID:26371612

[9] Hayama H, Fueki K, Wadachi J, Wakabayashi N. Trueness and precision of digital impressions obtained using an intraoral scanner with different head size in the partially edentulous mandible. J Prosthodont Res. 2018;62:347–52. https://doi.org/10.1016/j.jpor.2018.01.003, PMID:29502933

[10] Lee JH, Yun JH, Han JS, Yeo ISL, Yoon HI. Repeatability of intraoral scanners for complete arch scan of partially edentulous dentitions: an in vitro study. J Clin Med. 2019;8:1187. https://doi.org/10.3390/jcm8081187, PMID:31398851

[11] Sakamoto K, Wada J, Arai Y, Hayama H, Ishioka Y, Kim EY, *et al.* Effect of abutment tooth location on the accuracy of digital impressions obtained using an intraoral scanner for removable partial dentures. J Prosthodont Res. 2023;67:531–8. https://doi.org/10.2186/jpr.JPR_D_22_00201, PMID:36775339

[12] Kim EY, Wada J, Sakamoto K, Ishioka Y, Arai Y, Murakami N, *et al.* Effect of scanning origin location on data accuracy of abutment teeth region in digital impression acquired using intraoral scanner for removable partial denture: a preliminary in vitro study. J Clin Med. 2022;11:7392. https://doi.org/10.3390/jcm11247392, PMID:36556008

[13] Nagayama T, Wada J, Watanabe C, Murakami N, Takakusaki K, Uchida H, *et al.* Influence of retainer and major connector designs of removable partial dentures on the stabilization of mobile teeth: A preliminary study. Dent Mater J. 2020;39:89–100. https://doi.org/10.4012/dmj.2018-272, PMID:31582595

[14] Wada J, Wada K, Uctasli S, Wakabayashi N, Iwamoto T, Vallittu PK, *et al.* Effect of splinting material type and location on resistance against deflection force of splinted periodontally compromised teeth with hypermobility. J Mech Behav Biomed Mater. 2023;142:105873. https://doi.org/10.1016/j.jmbbm.2023.105873, PMID:37119722

[15] Schulte W, D'Hoedt B, Lukas D, Maunz M, Steppeler M. Periotest for measuring periodontal characteristics–Correlation with periodontal bone loss. J Periodontal Res. 1992;27:184–90. https://doi.org/10.1111/j.1600-0765.1992.tb01667.x, PMID:1608031

[16] International Organization for Standardization. ISO 12836:2015. Dentistry, Digitizing devices for CAD/CAM systems for indirect dental restorations, Test methods for assessing accuracy, https://www.iso.org/standard/68414.html; 2015 [accessed 17 December 2023].

[17] Diker B, Tak Ö. Comparing the accuracy of six intraoral scanners on prepared teeth and effect of scanning sequence. J Adv Prosthodont. 2020;12:299–306. https://doi.org/10.4047/jap.2020.12.5.299, PMID:33149851

[18] Luthardt RG, Koch R, Rudolph H, Walter MH. Qualitative computer aided evaluation of dental impressions in vivo. Dent Mater. 2006;22:69–76. https://doi.org/10.1016/j.dental.2005.02.015, PMID:16040117

[19] Laster L, Laudenbach KW, Stoller NH. An evaluation of clinical tooth mobility measurements. J Periodontol. 1975;46:603–7. https://doi.org/10.1902/jop.1975.46.10.603, PMID:1058939

[20] Shimizu T, Tasaka A, Wadachi J, Yamashita S. A new proposal for improving the accuracy of intraoral scanning for partially edentulous residual ridge. J Prosthodont Res. 2023;67:246–54. https://doi.org/10.2186/jpr.JPR_D_22_00088, PMID:36031353

[21] Kim JE, Amelya A, Shin Y, Shim JS. Accuracy of intraoral digital impressions using an artificial landmark. J Prosthet Dent. 2017;117:755–61. https://doi.org/10.1016/j.prosdent.2016.09.016, PMID:27863856

[22] Latham J, Ludlow M, Mennito A, Kelly A, Evans Z, Renne W. Effect of scan pattern on complete-arch scans with 4 digital scanners. J Prosthet Dent. 2020;123:85–95. https://doi.org/10.1016/j.prosdent.2019.02.008, PMID:30982616

[23] Hariri I, Sadr A, Nakashima S, Shimada Y, Tagami J, Sumi Y. Estimation of the enamel and dentin mineral content from the refractive index. Caries Res. 2013;47:18–26. https://doi.org/10.1159/000342416, PMID:23051596

[24] Ma Y, Guo Y, Saleh MQ, Yu H. Influence of ambient light conditions on intraoral scanning: A systematic review. J Prosthodont Res. 2023;68:237–45. https://doi.org/10.2186/jpr.JPR_D_23_00098, PMID:37574273

[25] Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig. 2014;18:1687–94. https://doi.org/10.1007/s00784-013-1132-y, PMID:24240949

[26] Flügge T, Att W, Metzger M, Nelson K. Precision of dental implant digitization using intraoral scanners. Int J Prosthodont. 2016;29:277–83. https://doi.org/10.11607/ijp.4417, PMID:27148990

[27] Frank RP. Analysis of pressures produced during maxillary edentulous impression procedures. J Prosthet Dent. 1969;22:400–13. https://doi.org/10.1016/0022-3913(69)90207-8, PMID:4898313

[28] Hyde TP, Craddock H, Brunton P. The effect of seating velocity on pressure within impressions. J Prosthet Dent. 2008;100:384–9. https://doi.org/10.1016/S0022-3913(08)60241-3, PMID:18992572

[29] International Organization for Standardization. ISO 4823:2021. Dentistry, Elastomeric impression and bite registration materials, https://www.iso.org/standard/73328.html; 2021 [accessed 30 April 2024].

[30] Suenaga K, Sato T, Nishigawa G, Minagi S. Relationship between size of denture foundation area and resorption of alveolar ridge in the edentulous mandible. J Oral Rehabil. 1997;24:315–9. https://doi.org/10.1111/j.1365-2842.1997.tb00333.x, PMID:9147306

[31] Carr AB, Brown DT. McCracken's clinical removable partial prosthodontics. 13th ed. St. Louis: Elsevier Mosby; 2015, p. 226-30.

[32] Al-Ahmad A, Masri R, Driscoll CF, Von Fraunhofer J, Romberg E. Pressure generated on a simulated mandibular oral analog by impression materials in custom trays of different design. J Prosthodont. 2006;15:95–101. https://doi.org/10.1111/j.1532-849X.2006.00081.x, PMID:16650009

[33] Schoen FJ, Mohammed H, Fischlschweiger W, Going RE. Objective evaluation of surface microreplication by dental impression materials. J Dent Res. 1978;57:283–90. https://doi.org/10.1177/00220345780570022401, PMID:277524

[34] Marcinak CF, Draughn RA. Linear dimensional changes in addition curing silicone impression materials. J Prosthet Dent. 1982;47:411–3. https://doi.org/10.1016/S0022-3913(82)80092-9, PMID:6951042

[35] Schulte W, Lukas D. The Periotest method. Int Dent J. 1992;42:433–40. https://europepmc.org/article/MED/1286926 PMID:1286926

[36] Ishioka Y, Wada J, Kim EY, Sakamoto K, Arai Y, Murakami N, *et al.* Morphological comparison of residual ridge in impression for removable partial denture between digital and conventional techniques: a preliminary in-vivo study. J Clin Med. 2023;12:7103. https://doi.org/10.3390/jcm12227103, PMID:38002714