Heliyon 9 (2023) e20403

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Measurement of proximal contact of single crowns to assess interproximal relief: A pilot study

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ARTICLE INFO

Keywords:
CAD-CAM
Crowns
Interproximal relief
Prosthesis fitting
Proximal surface adjustment

ABSTRACT

Background: It is common for dental technicians to adjust the proximal surface of adjacent teeth on casts when fabricating single crowns. However, whether the accuracy of the proximal contact is affected if this step is eliminated is unclear.
Objective: To evaluate the accuracy of the proximal contact of single crowns for mandibular first molars fabricated from four different restorative materials, without adjustment of the proximal surface of the adjacent teeth by the laboratory/dental technician.
Methods: This study was in vitro; all the clinical procedures were conducted on a dentoform. The mandibular first molar tooth on the dentoform was prepared using diamond burs and a high speed handpiece. Twenty single crowns were fabricated, five for each group (monolithic zirconia, lithium disilicate, metal ceramic, and cast gold). No proximal surface adjacent to the definitive crowns was adjusted for tight contact in the dental laboratory. Both the qualitative analyses, using dental floss and shimstock, and the quantitative analyses, using a stereo microscope, were performed to evaluate the accuracy of the proximal contact of the restoration with the adjacent teeth. In the quantitative analysis, one-way analysis of variance was used to compare mean values at a significance level of 0.05.
Results: In quantitative analysis, the differences between the proximal contact tightness of the four groups was not statistically significant ($P = 0.802$ for mesial contacts, $P = 0.354$ for distal contacts). In qualitative analysis, in most crowns, dental floss passed through the contact with tight resistance and only one film of shimstock could be inserted between the adjacent teeth and the restoration. However, one specimen from the cast gold crown had open contact.
Conclusions: Even without proximal surface adjustment of the adjacent teeth during the crown fabrication process, adequate proximal contact tightness between the restoration and adjacent teeth could be achieved.

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https://doi.org/10.1016/j.heliyon.2023.e20403
Received 10 March 2023; Received in revised form 23 August 2023; Accepted 22 September 2023

1. Introduction

Restoring a deeply carious tooth after root canal treatment or a cracked tooth with a crown is a predictable treatment option that yields high patient satisfaction [1]. However, despite the high survival and success rates, biological and technical complications associated with crowns are common [2]. Overly tight proximal contact results in incomplete marginal seating of crowns that can lead to open margins, inflammation of gingival tissue, and recurrent dental caries [3–7]. Loose interproximal contact is one of the most commonly reported complications, along with fracture of artificial crowns and chipping of restorative materials [2]. Loose interproximal contact between crowns and adjacent natural teeth may result in food impaction, which increases the risk of gingival tissue trauma, inflammation, and caries in the adjacent tooth [3,8,9]. Furthermore, patients are usually sensitive to food impaction, and it is a frequent complaint in dental clinics. Loose interproximal contact, and thereby food impaction, also cause discomfort during mastication. However, it has been reported that adjacent, natural, unrestored teeth at rest exhibit a space of up to 21 μm interproximally, which closes during clenching [8]. Therefore, interproximal contact tightness should be dynamically balanced to prevent food impaction and to allow an artificial crown to be completely seated.

Recently, some preliminary efforts have been devoted to exploring data-driven intelligent restoration methods which can be roughly categorized into computer graphics (CG)-oriented ones and deep learning (DL)-guided ones [10]. In CG-oriented methods, CAD-based dental restoration schemes are used, and in DL-guided methods, deep-learned models have been applied to dental image processing due to their superior performance [11–16]. For instance, Yuan et al. developed a Pix2Pix-based network for occlusal surface generation, and Hwang et al. applied an automatic approach based on the Pix2Pix model to design dental crowns by learning through statistical features [16–18]. However, these methods do not consider the dental biological morphology when reconstructing the occlusal surface, therefore the occlusal surface generated by these methods do not have the anatomical morphology of natural teeth [19]. It is notable that although some of these deep models may outperform CG-based methods, they are designed for specific dental tasks and are still limited in the aspect of manufacturing single dental crowns.

With the availability of large-scale training data and the development of training approaches, generative adversarial network (GAN) has demonstrated remarkable achievements in synthesizing realistic images by learning complex generative models [10, 20–22]. Recently, Tian et al. developed a new approach for dental crown prosthesis restoration, utilizing a two-stage deep generative adversarial network (DCPR-GAN), to address the issues in reconstructing the functional occlusal surface for defective teeth. This investigation showed that their proposed framework significantly outperforms the state-of-the-art deep learning methods in functional occlusal surface reconstruction using a real-world patient database [19]. In a previous study, Tian et al. had developed a computer-aided deep adversarial-driven dental inlay restoration (DAIS) framework, which automatically reconstructed a realistic surface for a defective tooth. DAIS efficiently processed large areas of missing teeth with arbitrary shapes, generating realistic occlusal surface completions [10].

Utilizing the learning capabilities of deep neural networks to rebuild missing teeth from incomplete dental models, Zhu et al. proposed a two-stage approach known as ToothCR. This approach uses a novel surface reconstruction algorithm to restore the surface of the predicted missing tooth [23]. In another study, Feng et al. introduced a novel method for automatic reconstruction of a three-dimensional model of the maxillary anterior tooth crown. This method involves a pose estimation network (PEN) and a shape estimation network (SEN) to jointly estimate the crown point cloud. The iterative method is then used to form the crown mesh model based on the point cloud. Results indicated the promising potential of this method, as the method requires less than 11 s to reconstruct a case [24]. Despite these advancements, however, it should be noted that conventional techniques still maintain their relevance, and many technicians continue to rely on conventional crown fabrication methods.

Fabrication of conventional cast gold restorations involves a series of steps. A die stone is prepared and the technician sections the model to build a wax pattern. The wax pattern is then sprued, invested in a gypsum-bonded investment, and cast in gold alloy by using the standard lost-wax technique [25]. The lost-wax process for fabricating cast gold restorations was introduced by W. Taggert in 1907 [26]. Producing precise and well-fitting cast gold restorations is challenging for both clinicians and dental laboratories. Contributing to this challenge is the issue of wax pattern distortion during the fabrication process and other errors that may lead to proximal contact inaccuracies, thereby affecting the seating of restorations [27,28].

We are currently in the era of routinely providing all-ceramic restorations because of newly available materials such as zirconia-based ceramic materials and lithium disilicate [29]. In addition, newer fabrication systems such as computer aided design and computer aided manufacturing (CAD-CAM) are becoming widely available [30–33]. Dental technology that was previously centered on the standardized lost-wax casting technology has been greatly improved with the introduction of dental CAD-CAM systems [34].

Recently, a study by Chen et al. reported significant differences between AI-generated and technician's CAD-designed crowns in several parameters of occlusal morphology including profile discrepancy. They concluded that CAD design by humans may be better than knowledge-based AI [35]. Another study by Ding et al. utilized 3D-Deep Convolutional Generative Adversarial Network (3D-DCGAN), which is a true 3D machine learning method, to design dental crowns and then comparing the crowns to CEREC Biogeneric individual design and technician CAD design operated by an experienced dental technician. They concluded that 3D-DCGAN could be used to design personalized dental crowns that accurately mimic both the morphology and biomechanics of natural teeth, in this case mandibular second premolars were used; producing a similar fatigue lifetime to natural teeth as well. Designs done by a technician yielded a lower fatigue lifetime compared to natural teeth [36].

However, conventional fabrication techniques are still considered effective and reliable for the fabrication of precise dental prostheses. CAD-CAM is only partially applied and is currently limited to laboratory processing. For example, even if the zirconia framework is fabricated using a CAD-CAM process, final restorations are completed using conventional manual dental technology by dental technicians [37]. In cases where the dental technician adjusts or lightly scrapes the proximal surfaces of adjacent teeth on the cast when fabricating zirconia or lithium disilicate restorations, the natural contour and space between the teeth may be affected when seating the final restoration [38]. To date, few studies have evaluated this aspect of crown fabrication.

This study aimed to evaluate the accuracy of proximal contact of single crowns for mandibular first molars fabricated from four different restorative materials without the laboratory procedure of adjusting the proximal surface of the adjacent teeth for tight proximal contact. Traditional gold alloys, feldspathic porcelain, lithium disilicate, and monolithic zirconia were used. The null hypothesis of this study was that no differences would be found in the interproximal contacts between the four types of restorative materials. The data were clinically interpreted in the context of laboratory intervention for tight proximal contacts.

2. Methods

All study clinical procedures were performed on a dentoform. Standard guidelines for tooth preparation were established in this study. For the convenience of fabricating future prosthesis, the margin was set at the equigingival level, and the corresponding area was marked with a black line. To avoid damaging the proximal surfaces of the adjacent teeth, the mandibular right first molar of the dentoform was removed from the typodont during the abutment preparation process. Tooth preparation was performed using round-end tapered diamond burs (Mani, Inc.) in a high-speed rotary handpiece with water coolant (M9000 L; KaVo Dental). After tooth preparation was completed, the mandibular right first molar was screwed back onto the typodont. Impressions were taken using heavy- and light-body impression materials (Examix; GC Corporation), and a master model was fabricated.

2.1. Duplication of the model

To duplicate the definitive cast, silicone molds were fabricated. Two molds for duplication purposes were fabricated by first placing the previously produced definitive cast on a flat surface with baseplate wax surrounding it. Zhermack's Elite Double #22 (medium) base and catalyst were mixed well, poured into this makeshift mold, and removed after it hardened sufficiently. The silicone mold was then examined for air bubbles. After confirming that the margin area was accurately replicated on the silicone mold, 10 casts were fabricated from each mold using dental stone.

2.2. Fabrication of artificial crowns

A dental technician with 10 years of experience was commissioned to fabricate a total of 20 crowns, five crowns each of monolithic

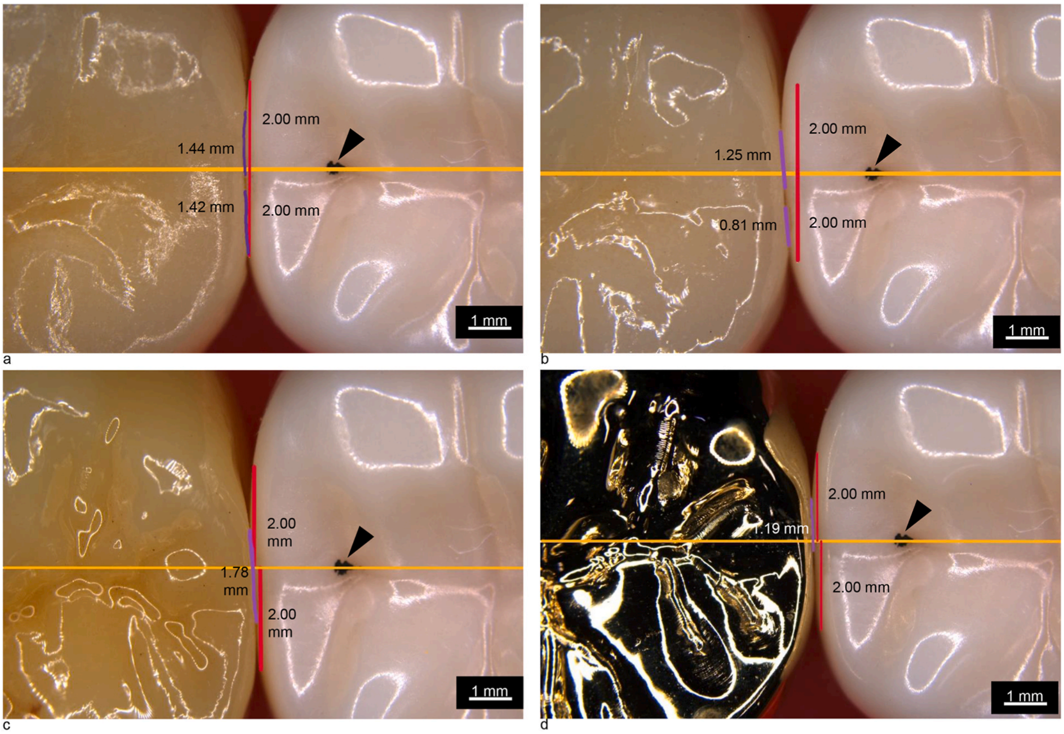

Fig. 1. Representative images of quantitative measurement of interproximal contact tightness. a. Monolithic zirconia. b. Lithium disilicate. c. Metal ceramic. d. Cast gold. Yellow lines are the lines running through the reference points, i.e., the centers of the distal fossa of the mandibular right second premolar and the mesial fossa of the mandibular right second molar (black arrowheads). Red lines are vertical to these yellow reference axes (each 2 mm in length). Purple lines are the contact lengths measured on the images.

zirconia, lithium disilicate, metal ceramic, and cast gold. A digital approach was used for the monolithic zirconia crowns. A model scanner (T710; Medit Corp.) was used to scan the master models. The definitive crowns were made with monolithic zirconia (Perfit ZR™; Vatech mcis Corp.) using CAM (ARUM 5X-150; Doowon Corp.). This digital methodology ensures the production of monolithic zirconia crowns with consistent and uniform quality [29]. For the lithium disilicate crowns, the heat-pressing technique was used [39]. Wax patterns were prepared, and lithium disilicate ingots (E.max press; Ivoclar Vivadent) were heat pressed for the definitive crowns. This method is widely recognized for its ability to produce accurate and aesthetic lithium disilicate crowns [5]. For the metal ceramic group, gold alloy copings (GP92; Sungbo Co., Ltd.) were fabricated by casting, and feldspathic porcelain (CZR; Kuraray Noritake Dental Inc.) was applied following the conventional method [5]. This approach is a well-established method for the fabrication of an aesthetic and durable crown [5]. The cast gold crowns, which served as control, were made using the traditional lost-wax technique, which is another well-established and conventional approach for making artificial prosthodontic crowns. The lithium disilicate, metal ceramic, and cast gold crowns were made on the master dies, whereas the monolithic zirconia crowns were made digitally. To prevent bias, the purpose of the experiment was not disclosed to the dental technician. The technician was also instructed not to flatten the proximal surface of the adjacent teeth, which is usually done to ensure tight contact. The entire fabrication took 3 weeks.

2.3. *Measurement of proximal contact tightness*

The proximal contact tightness was measured using two types of measurements: quantitative and qualitative. For quantitative measurement, the amount of surface in contact with the adjacent tooth was evaluated using a stereoscopic microscope (Stereozoom S9D; Leica Microsystems). Initially, the upper and lower arches of the dentoform were separated to facilitate observation. Measurements were taken from an occlusal perspective. To establish consistent reference points, markers were placed on the distal central fossa of the mandibular right second premolar and the mesial central fossa of the mandibular right second molar. A horizontal line was drawn, intersecting the middle of the distal fossa of the mandibular right second premolar and the mesial fossa of the mandibular right second molar, serving as a reference axis. Two perpendicular vertical lines, each measuring 2 mm, were placed above and below this line. The mesial and distal contact areas of the crown and adjacent teeth were measured and captured using the stereo microscope under constant magnification (Fig. 1).

For qualitative measurement, the degree of resistance when passing a strand of waxed dental floss (Oral B Essential Floss) with a thickness of approximately 0.01 mm–0.05 mm and shimstock through the contacts was evaluated. The degree of resistance was classified as tight and loose for the dental floss test, and the number of sheets of shimstock passed through the contacts was recorded for the shimstock test. Fig. 2 summarizes the experimental design.

2.4. *Statistics*

Quantitative data were statistically analyzed with R software (v.4.2.2; R Foundation for Statistical Computing). The data obtained in the quantitative measurement were presented as mean ± standard deviation (SD). One-way analysis of variance was used to compare mean values between the restoration materials. Statistical significance was set at $p < 0.05$.

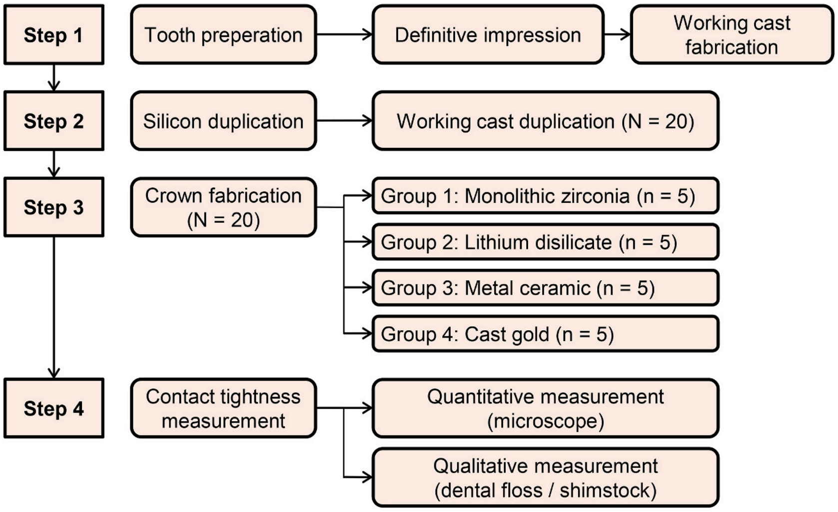

Fig. 2. Flow chart of this study. The study was conducted in four stages. In the first stage, crown preparation was done for the corresponding tooth on the dentoform and a master model was made. In the second stage, silicone molds were fabricated for duplication of the master model. In the third stage, four groups of crowns of varying materials were fabricated from the duplicated casts. In the last stage, proximal contact accuracy was evaluated using quantitative and qualitative methods.

3. Results

3.1. Quantitative analysis

In the quantitative analysis, the difference between the proximal contact tightness of the four groups was not statistically significant ($p = 0.802$ for mesial contacts, $p = 0.354$ for distal contacts) (Table 1). In sample No. 1 of the cast gold crown group, the mesial and distal proximal surfaces were not in contact with the adjacent teeth when observed using the stereo microscope. Because the contact was open, the corresponding proximal contact tightness was not measured. Although no statistical significance was observed in each group, the metal ceramic crowns showed the highest values, which suggests that a greater amount of porcelain was layered compared to the amount of wax removed during the heat-pressing or casting process. A limitation of using a stereoscopic microscope for measurements was the inability to accurately observe the three-dimensional shape of the crowns in a two-dimensional photograph. Furthermore, the individual crowns had varying shapes, and their contours along the vertical axis were different. In cases where the height of the ridge differed between teeth, even if they appeared to be in contact with each other in the two-dimensional photograph taken with the stereoscopic microscope, there may have been instances where they were not actually in contact.

3.2. Qualitative analysis

Qualitative analysis was performed to reduce the aforementioned errors (Table 2). In qualitative analysis, the dental floss passed through with tight resistance in most crowns. In the shimstock test, only one film could pass through the proximal contact of the crowns, except in the case of one gold crown. The technician in this study was found to fabricate crowns with quite tight proximal contacts despite no adjustment of the proximal surface. The qualitative analysis showed a similar trend to the quantitative analysis in terms of contact data, although a correlation test was inapplicable. However, as mentioned earlier, visual errors arising from variations in the height of tooth ridges were a possibility. In other words, it was observed that qualitative measurement results differed even when the contact lengths appeared to be similar.

4. Discussion

Many studies have been conducted on the accuracy of interproximal contact of crowns. However, to the authors' knowledge, no study similar to this study was found with respect to evaluation of the proximal contact from an occlusal view. The null hypothesis that no significant differences would be found in the interproximal contacts among these four restorations was accepted.

According to current clinical guidelines, contacts of restored proximal surfaces should be adjusted until microscopic clearance or passive contact with the adjacent tooth, interproximal relief, is achieved [38]. Generally, a satisfactory contact allows a dental floss to pass interdentally with firm resistance. Conventional techniques for clinically evaluating and adjusting interproximal contacts include using dental floss, Mylar shimstock dental films, and Mylar articulation films. Tooth contacts should not be too tight or too open [6]. A space of 13 μm between natural teeth has been found in 80%–90% of interproximal contacts [28]. However, the use of dental floss may not be the best method to evaluate proximal contact, because when the floss passes through the contact, opening of the interproximal

Table 1

Quantitative measurements of proximal contact tightness.

M-ZrO$_2$[a]	mesial		distal		LD[b]	mesial		distal	
	mm	%	mm	%		mm	%	mm	%
1	2.29	57.2	1.24	31.0	1	0.64	16.0	2.40	60.0
2	0.88	0.22	2.06	51.5	2	0.82	20.5	1.97	49.3
3	1.25	31.3	2.00	50.0	3	2.88	72.0	1.41	35.3
4	2.07	51.8	1.26	31.5	4	2.57	64.3	2.86	71.5
5	1.61	40.3	1.95	48.8	5	0.61	15.3	2.64	66.0
mean	1.62	36.2	1.70	42.6	mean	1.50	37.6	2.26	56.4
SD	0.58	22.5	0.41	10.4	SD	1.12	28.1	0.58	14.4
MC[c]	mesial		distal		Au[d]	mesial		distal	
	mm	%	mm	%		mm	%	mm	%
1	2.00	50.0	1.65	41.3	1	–	–	–	–
2	2.49	62.3	1.01	25.3	2	1.51	37.8	2.27	56.8
3	1.86	46.5	1.78	44.5	3	1.89	47.3	1.89	47.3
4	0.75	18.8	0.86	21.5	4	0.58	14.5	2.92	73.0
5	1.90	47.5	2.28	57.0	5	1.24	31.0	1.19	29.8
mean	1.80	45.0	1.52	37.9	mean	1.31	32.6	2.07	51.7
SD	0.64	16.0	0.58	14.6	SD	0.55	12.0	0.72	15.6

[a] Monolithic zirconia crowns.

[b] Lithium disilicate crowns.

[c] Metal ceramic crowns.

[d] Cast gold crowns.

Table 2
Qualitative measurements of proximal contact tightness.

M-ZrO$_2$[a]	mesial		distal		LD[b]	mesial		distal	
	D.F[e]	S.S[f]	D.F	S.S		D.F	S.S	D.F	S.S
1	tight	0	loose	0	1	loose	0	tight	0
2	loose	1	tight	0	2	loose	1	tight	0
3	loose	1	tight	0	3	tight	0	tight	0
4	tight	0	loose	0	4	tight	0	tight	0
5	tight	0	tight	0	5	loose	1	tight	0
MC[c]	mesial		distal		Au[d]	mesial		distal	
	D.F	S.S	D.F	S.S		D.F	S.S	D.F	S.S
1	tight	0	tight	0	1	open	–	open	–
2	tight	0	tight	0	2	tight	0	tight	0
3	tight	0	tight	0	3	loose	0	tight	0
4	loose	0	loose	1	4	loose	1	tight	0
5	tight	0	tight	0	5	loose	0	loose	1

[a] Monolithic zirconia crowns.
[b] Lithium disilicate crowns.
[c] Metal ceramic crowns.
[d] Cast gold crowns.
[e] Dental floss.
[f] Shimstock (8 μm thick).

contact can be visibly seen upon air-drying and inspection [28,40]. Tight contacts frequently result in open crown margins. A study by Harper et al. revealed that tight or binding contact with the shimstock represents a gap of less than 6 μm. Resistance and binding while pulling the shimstock represents a gap of approximately 6 μm, and only light resistance while pulling the shimstock corresponds to a gap of 8 μm. Therefore, 8 μm shimstock was used in this study [41]. The shimstock or Mylar articulating film should pass between teeth with slight resistance. If it binds, adjustments should be made, followed by reassessment to verify proper interproximal contact [40].

In a previous study, an ultrathin (less than 0.05 mm) abrasive diamond strip was used to adjust the proximal contact and provide relief from pressure in the interproximal space (interproximal relief). Conventionally, the proximal contacts of indirect restorations are marked using an articulating film and adjusted with rotary instruments. However, diamond strips offer tactile control and reduce chair-side time [38]. The interproximal relief technique involves the adjustment of proximal contact surfaces of a restoration by a clinician in the patient's mouth. Initially, this restoration is fabricated by a dental technician at a dental laboratory. Consequently, if the dental technician establishes tight proximal contacts for the restoration through contact adjustment of the real or virtual die, it can significantly extend the duration of the interproximal relief procedure, making the procedure more challenging to perform. Thus, the results of this study suggest that refraining from adjusting the adjacent proximal surface on the master die or software in a dental laboratory may further decrease chair time. Such an approach contributes to enhancing patient comfort by minimizing the procedure time. These clinical and laboratory skills will help reduce and eliminate commonly occurring proximal contact issues [7].

Based on the results of this study, CAD-CAM restorations showed adequate interproximal contact and binding when floss and shimstock were passed through. However, open contact was observed in one cast gold crown. This implies that even without prior adjustment of proximal surfaces by the dental technician on the software, the interproximal accuracy was acceptable [33].

The present study has several limitations. This study was an in vitro investigation with a small sample size, implying that further studies with large sample sizes are needed, which are more similar to clinical situation. Additionally, it is crucial to compare an experimental group where the non-adjustment of proximal surfaces on the master cast is implemented with a control group that follows the conventional practice of adjusting these surfaces. Moreover, the crown preparation of the mandibular right first molar dentoform tooth was performed outside of the typodont, which may not have completely replicated the clinical conditions. When viewing under the microscope, pixelation occurs during enlargement of the image while taking measurements. Furthermore, the typodont position could not be fixed, and slight movements may have occurred while obtaining the measurements, which may have further impacted measurement accuracy. To address these limitations and improve the study's repeatability, future research should explore the integration of deep learning and three-dimensional based models, incorporating improved study designs. Also, using coordinate measuring machine could ensure reproducibility of experiments by facilitating more complex observation [42]. These advancements will aid in finding a more standardized and reliable method of measurement. In addition, studies are needed to separately evaluate various factors affecting the difference in proximal contact strength, including restoration materials, fabrication techniques, and long-term mastication.

5. Conclusion

Based on the findings of this study, the following conclusions were drawn: It is unnecessary for dental technicians to adjust the proximal surface of the master die teeth adjacent to the definitive crowns for tight contact to prevent food impaction. Such adjustments may hinder the complete seating of definitive restorations, which clinically leads to secondary caries. Digital manufacturing technology, such as CAD-CAM for monolithic zirconia, may produce excellent artificial crowns with proper proximal contacts without any proximal adjustment of adjacent teeth on the software for tight interproximal contacts. However, considering the limitations inherent in this study, further research involving larger sample sizes and a standardized quantitative measurement method should be conducted. Additionally, investigations incorporating deep learning models deserve further exploration.

Funding statement

This study was supported by a grant from the Seoul National University School of Dentistry Fund [860–20220058].

Author contribution statement

Daniel S. Kim: Conceived and designed the experiments; Performed the experiments; Wrote the paper. Le Na Lau: Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Jong-Woong Kim: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. In-Sung Luke Yeo: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. Material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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