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RESEARCH AND EDUCATION

Determining the retention of removable partial dentures

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ABSTRACT

Statement of problem. Removable partial dentures (RPDs) provide a cost-effective treatment for millions of partially edentulous patients worldwide. However, they often fail because of loss of retention. One reason for this problem is lack of precise guidelines for designing retentive RPDs.

Purpose. The purpose of this in vitro study was to determine the forces produced by food and clasps during mastication to develop an algorithm for predicting RPD retention and to help determine the optimal number of clasps.

Material and methods. The forces that food exerts on acrylic resin teeth during simulated mastication and the retention forces provided by clasps (wrought wire, circumferential, and I-bar) engaging on teeth were measured using a universal testing machine. A statistical analysis was performed with a 1-way ANOVA and repeated-measures ANOVA while the developed algorithm was evaluated by using sensitivity and specificity analysis.

Results. The force exerted by food mastication on each individual tooth ranged between 1.7 and 12.2 N, depending on the type of tooth, tooth anatomy, occlusion, and food. The retention force of the clasps after cyclic testing ranged between 2.9 and 14.5 N, depending on the type of tooth abutment and clasp. Using these measurements, an algorithm was developed to predict RPD retention. The algorithm was confirmed experimentally on 36 RPDs, showing a sensitivity of 96%, specificity of 100%, and an accuracy of 97%.

Conclusions. The forces generated by food mastication on teeth varied according to the type of tooth, occlusion, and food. The retention force of RPD clasps varied according to the type of tooth and clasp. An algorithm for predicting RPD retention and determining the optimal number of clasps was developed and validated experimentally. (J Prosthet Dent 2019;122:55-62)

Removable partial dentures (RPDs) are cost-effective and functional dental prostheses that are used to restore missing teeth in partially edentulous patients.[1,2] An RPD is a treatment option that can improve the quality of life for millions of patients worldwide; over 13% of the adult population in North America and Europe wear RPDs.[3,4] However, many complications are associated with RPDs, mainly related to inadequate quality and poor design.[1,5,6] Indeed, poor RPD design results in insufficient retention, which is the main reason for treatment failure and patient dissatisfaction.[5-7]

Designing RPDs is challenging because there are 65 534 possible forms of partial edentulism, and the available design guidelines lack scientific evidence and do not cover all edentulism forms.[2,8,9] Therefore, RPDs are designed subjectively based on the experience of dental professionals, which could often result in inadequate designs.[10] In fact, many dentists delegate design work to dental technicians due to their extensive design experience.[11] Knowledge-based systems are available for designing RPDs that provide the most appropriate RPD design based on a database of previous patients.[10,12] However, RPD designs in the database might be inadequate and inappropriate because they were designed subjectively based on operator experience.

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Clinical Implications

The guidelines developed in this study may help predict RPD retention and determine the optimal number of clasps in an RPD.

A properly designed RPD should provide sufficient retention to resist the dislodging forces caused during food mastication and functional muscle movements; this can be achieved by retentive elements engaging the abutment teeth, including clasps, proximal plates, and rests or by attachment on dental implants.[2,5,9,13] However, most commonly, retention in RPDs is provided by clasp designed in a variety of forms (such as I-bar and circumferential clasp) and materials (such as wrought wire, cast metals, or acrylic resin).[2,9] Frank et al suggested that the retention of a clasp in an RPD should be between 3 and 7.5 N.[14,15] However, this can vary according to the clasp form, location, undercut depth, composition, and guide planes.[13,14,16] Accordingly, retention can be improved by optimizing the shape, undercut depth, and fabrication process.[16-19] For instance, clasps made with laser-sintering technology present better fatigue resistance and higher precision than cast clasps.[20,21]

RPD dislodgment occurs because of the force that pulls food away from the teeth from the action of adherent foods.[13,22] This force depends on factors such as patient masticatory habits, occlusion, tooth anatomy, and food characteristics such as size, shape, and texture.[13,22,23]

A common question raised in designing an RPD is determining the adequate number of clasps to provide sufficient retention to resist the dislodging forces caused during food mastication. RPDs with too few clasps could result in insufficient retention, whereas RPD with too many clasps could cause harm to the patient. Currently, guidelines to determine the optimal number of RPD clasps are lacking, as is the optimal amount of retention needed to achieve a retentive RPD. Therefore, determining the optimal retention of any RPD design, and whether it is sufficient or not, is the key to developing better design guidelines. Accordingly, the hypothesis of this study was that for an RPD to be retentive during mastication, the retention forces provided by its clasps should be higher than the dislodging forces generated by food. The purpose of this study was to determine the forces produced by food and clasps during mastication to develop an algorithm for predicting RPD retention and help determine the optimal number of clasps. Subsequently, this study aimed to validate the new algorithm for predicting RPD retention experimentally.

MATERIAL AND METHODS

The force that food exerts on acrylic resin teeth was measured by simulated mastication using a dentoform model (Nissin Dental Products Inc) fixed on a universal testing machine (Instron Corp) set at a constant mastication speed of 5 mm/second (Fig. 1; Supplemental Fig. 1).[24] The dentoform model allows placing or removing each tooth on the model separately, which helped in assessing all tooth types in both the arches. The force exertion by masticating caramel candy on anatomic teeth occluding in class 1 occlusion was conducted for every tooth separately on both the arches with 15 repetitions per tooth. Furthermore, other types of food, tooth anatomy, and occlusion were tested for all teeth in both the arches, and the tests were repeated 15 times for each type of food, tooth anatomy, and occlusion.

The types of tested food included caramel candy (Werther's original), chewing gum (Wrigley's Excel), and toasted bread (Villaggio) and were chosen based on a previous study that evaluated the stickiness of 21 different food items.[25] The impact of tooth anatomy was also assessed using anatomic and nonanatomic acrylic resin teeth.

To assess the impact of occlusion on simulated mastication, the dental arches were positioned and adjusted to be at class 1, 2, and 3 occlusions. Class 1 occurs when the maxillary teeth slightly overlap the mandibular teeth, class 2 when the maxillary teeth severely overlap the mandibular teeth, and class 3 when the mandibular teeth overlap the maxillary teeth.[26]

The retention forces of wrought wire, circumferential, and I-bar clasps engaging undercuts in each tooth type in both the arches were measured. Because of their flexibility, wrought wire clasps usually engage deeper undercuts (0.50 mm) than Co-Cr circumferential and I-bar clasps (0.25 mm).[18,27] For wrought wire clasps, 3 test specimens per tooth type were fabricated on partially edentulous casts duplicated from a dentoform model with a silicone impression material (Exaktosil N21; Bredent GmbH) and dental stone (Fig. 2). Each test specimen contained a pair of wrought wire clasps (17 GA; Keystone Dental Inc) placed at an undercut depth of 0.5 mm, an acrylic resin denture-base (Biocryl Resin Acrylic; Great Lakes Ortho Inc), and an attachment to the testing machine. For the circumferential and I-bar clasps, Co-Cr clasps were designed at undercut depths of 0.1 mm on the duplicated scanned model of the dentoform using a 3D scanner and a computer-assisted design (CAD) software (3Series; Dental Wings Inc) and processed by direct laser-sintering technology (Phenix PXM) at the prototyping center (3DRPD Inc).[20]

To test retention forces, the specimens were attached to the upper grip of a universal testing machine (Instron

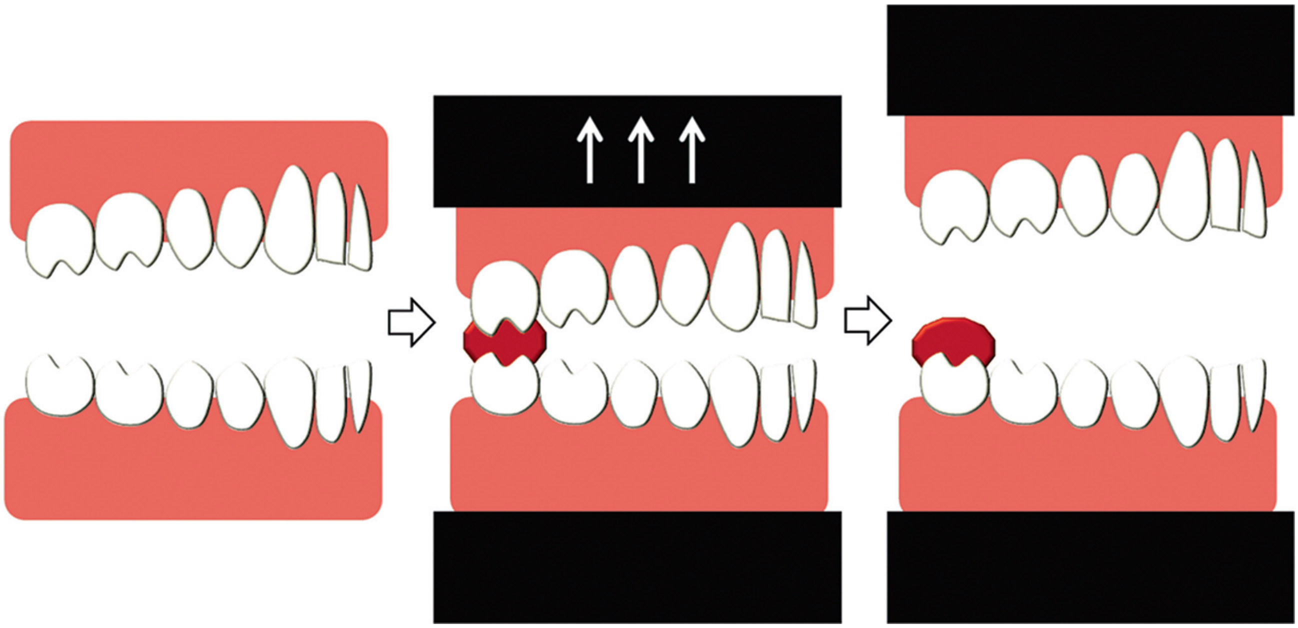

Figure 1. Testing of masticatory tensile forces.

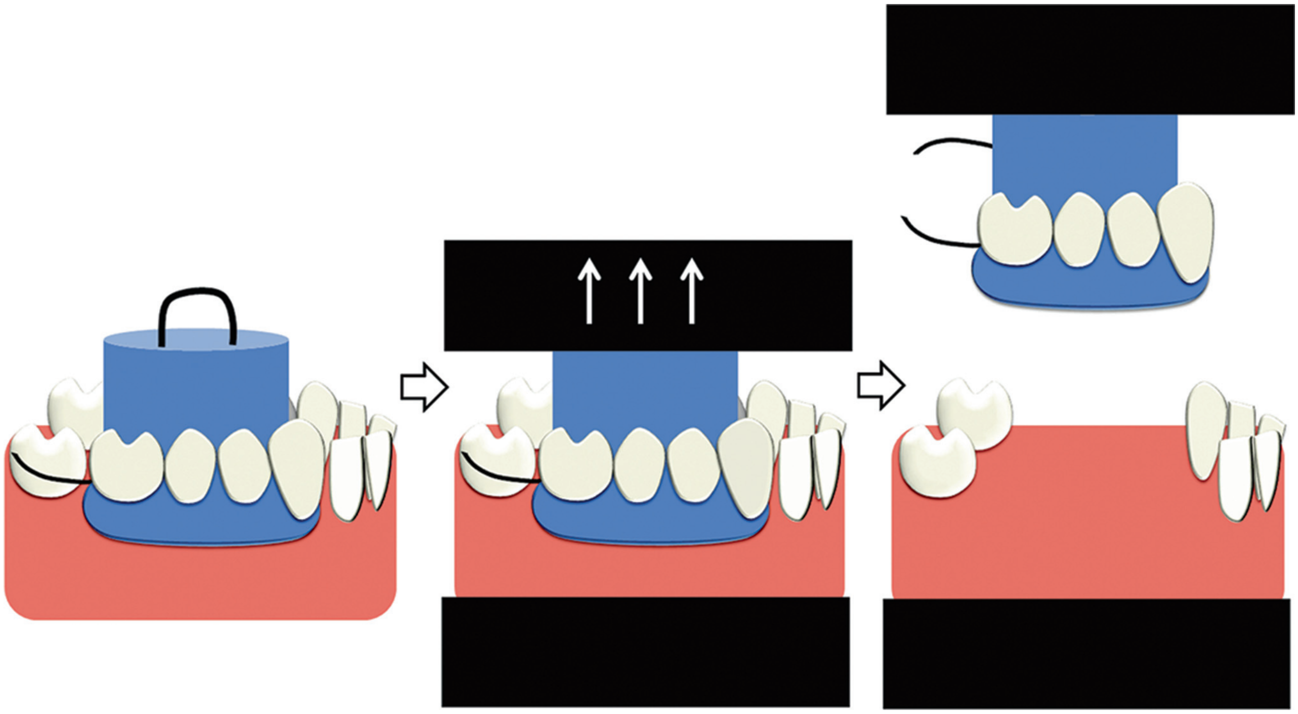

Figure 2. Testing of retention force for removable partial denture clasps.

Corp) and placed on the dentoform model that was fixed on the lower grip of the machine (Fig. 2 and Supplemental Figs. 2, 3). The machine applied a pull-out force at a constant speed of 5 mm/second until the clasps disengaged from the abutment teeth. The retention force was recorded, and the process was repeated 5 times for each test. Cyclic testing was applied manually by inserting and removing the clasps from the abutment teeth for up to 1200 cycles, which is the equivalent to wearing dentures for 1 year[28-30] The retention force after 1200 cycles was then recorded as described earlier.

An algorithm for predicting RPD retention was developed based on the hypothesis of this study by using the measurements from food mastication and clasp retention.

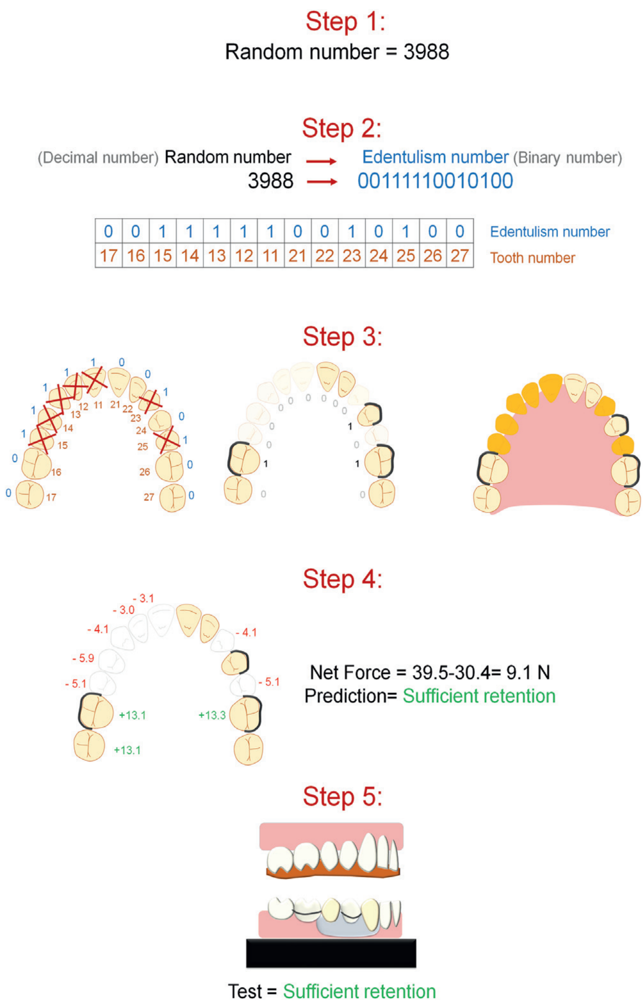

Figure 3. Example of selection and testing of random edentulous arches for algorithm validation. Step 1: selection of random number between 1 and 16 384. Step 2: converting random number into edentulous arch (binary number) in which 1 represents missing tooth and 0 represents tooth. Step 3: determining clasp location and fabricating removable partial denture. Step 4: determining retention prediction by using algorithm. Step 5: testing retention performance of removable partial denture.

$$\text{RPD retention force} = \sum \text{clasp retention force} - \sum \text{dislodging force on replaced tooth} \quad \text{(Equation 1)}$$

This equation calculates the net retention force of any RPD design and therefore can predict its retention performance. Based on that, a net retention force greater than zero indicates sufficient retention, whereas a negative value indicates insufficient retention.

A validation test was performed to test the accuracy of the algorithm for predicting RPD retention. A total of 36 random RPDs were tested (18 per arch). The mechanism of the selection and testing is summarized in Figure 3. First, because there are 16 384 possible forms of partial edentulism per arch, 36 random numbers were selected from 1 to 16 384 by using a random-number generator (www.random.org). The selected numbers were then converted to a binary number representing an edentulous arch where 1 represented missing teeth and 0 represented present teeth. The randomly edentulous partial arches with fewer than 2 remaining or missing teeth were excluded from the study because these edentulous arches should not be treated with an RPD. The selected random numbers and randomly generated edentulous arches are shown in Table 4.

Then, acrylic resin RPDs were subjectively designed and fabricated for the selected edentulous arches. This was performed on a master cast duplicated from the dentoform model as described previously. Finally, the experimental retention performances of the 36 RPDs were blind tested in simulated mastication with caramel candy as previously described. The RPDs that retained the original position during mastication were considered to have sufficient retention, whereas those displaced from their position were considered to have insufficient retention. The experimental results were then compared with those generated by the algorithm for predicting RPD retention.

Statistical analysis to identify differences between teeth for the forces produced by food and clasps was performed using a 1-way ANOVA, followed by the post hoc Tukey honestly significant difference test. A repeated-measures ANOVA was used to analyze the differences among the forces exerted by caramel candy mastication for class 1 occlusion under different mastication conditions and between clasp retention forces after 1 and 1200 cycles. Statistical software (IBM SPSS Statistics, v23.0; IBM Corp) was used for the analysis (α=.05). The sample size for the validation of the algorithm for predicting RPD retention was calculated at a confidence interval of 95%, design prevalence of 10%, unit specificity of 100%, and unit and required population sensitivity of 95%. Statistical analysis for the validation of the algorithm was performed with sensitivity and specificity analysis.[31]

RESULTS

The forces that food exerted on teeth varied depending on the type of tooth, occlusion, and food. The forces of caramel candy mastication on each anatomic tooth type in class 1 occlusion are shown in Table 1. The highest force generated by caramel candy mastication was recorded for the first molars in both the maxillary (12.0 ±0.7 N) and mandibular arches (12.2 ±1.1 N), whereas the lowest force was recorded on the mandibular lateral incisors (1.7 ±0.6 N). The forces exerted by caramel candy mastication were significantly different among tooth type (P<.001); molars and premolars (12.2 to 4.7 N) showed higher forces (P<.001) than canines and incisors (4.1 to 1.7 N).

Table 1. Masticatory tensile forces generated by mastication of caramel candy on different types of anatomic tooth at occlusion class 1 in both arches

Arch	Tooth	Masticatory Tensile Forces (N)	*P* Values for Post hoc Comparison Among Tooth Type						
			Central	Lateral	Canine	First Premolar	Second Premolar	First Molar	Second Molar
Maxillary	Central	3.1 ±0.6	–	.999	.002	<.001	<.001	<.001	<.001
	Lateral	3.0 ±0.4	.999	–	<.001	<.001	<.001	<.001	<.001
	Canine	4.1 ±0.6	.002	<.001	–	<.001	.004	<.001	<.001
	First premolar	5.9 ±0.9	<.001	<.001	<.001	–	.023	<.001	<.001
	Second premolar	5.1 ±0.8	<.001	<.001	.004	.023	–	<.001	<.001
	First molar	12.0 ±0.7	<.001	<.001	<.001	<.001	<.001	–	<.001
	Second molar	10.1 ±0.9	<.001	<.001	<.001	<.001	<.001	<.001	–
Mandibular	Central	3.1 ±0.9	–	<.001	.709	<.001	<.001	<.001	<.001
	Lateral	1.7 ±0.6	<.001	–	<.001	<.001	<.001	<.001	<.001
	Canine	3.6 ±0.6	.709	<.001	–	<.011	<.001	<.001	<.001
	First premolar	4.7 ±0.9	<.001	<.001	<.011	–	.683	<.001	<.001
	Second premolar	5.3 ±0.7	<.001	<.001	<.001	.683	–	<.001	<.001
	First molar	12.2 ±1.1	<.001	<.001	<.001	<.001	<.001	–	.975
	Second molar	11.9 ±1.2	<.001	<.001	<.001	<.001	<.001	.957	–

Table 2. Masticatory tensile forces exerted by different types of food on arch depending on tooth anatomy and type of occlusion

Arch	Tooth	Tooth Anatomy	Occlusion	Food Type	Masticatory Tensile Forces (N)	*P*
Maxillary	All teeth	Anatomic	Class 1	Caramel	51.6 ±5.8	reference
			Class 2		49.6 ±2.4	<.001
			Class 3		46.8 ±4.0	.003
		Nonanatomic	Class 1	Caramel	45.4 ±1.7	<.001
		Anatomic		Gum	16.5 ±1.3	
				Bread	6.2 ±1.0	
Mandibular	All teeth	Anatomic	Class 1	Caramel	49.6 ±2.6	reference
			Class 2		40.0 ±2.8	<.001
			Class 3		41.0 ±3.2	
		Nonanatomic	Class 1	Caramel	45.2 ±2.6	
		Anatomic		Gum	15.6 ±1.2	
				Bread	5.9 ±0.9	

The force exerted by caramel candy on mastication in class 1 occlusion in the entire maxillary and mandibular arch (51.6 ±5.8 N in maxillary arch; 49.6 ±2.6 N in mandibular arch) was higher (*P*<.001) when the teeth had anatomic occlusal surfaces than when they had nonanatomic occlusal surfaces (45.4 ±1.7 N in maxillary arch; 45.2 ±2.6 N in mandibular arch) (Table 2). Mastication with class 1 occlusion produced higher force than class 3 occlusion in the maxillary arch (46.8 ±4.0 N; *P*=.003) and mandibular arch (41.0 ±3.4 N; *P*<.001) and class 2 occlusion in the mandibular arch (40.0 ±2.8 N; *P*<.001). Also, the mastication of caramel candy produced higher force (*P*<.001) than the chewing gum (16.5 ±1.3 N in the maxillary arch; 15.6 ±1.2 N in the mandibular arch) and bread (6.2 ±1.0 N in the maxillary arch; 5.9 ±0.9 N in the mandibular arch).

The retention forces of wrought wire, circumferential, and I-bar clasps engaging on teeth are shown in Table 3. The highest retention force with wrought wire and circumferential clasps was recorded on molars (14.5 ±1.7 N and 6.8 ±1.0 N), whereas the lowest retention force was recorded on incisors (8.5 ±1.6 N and 2.9 ±1.2 N). The retention forces of wrought wire and circumferential clasps were significantly (*P*<.001) different depending on the type of tooth (Table 3 and Supplemental Tables 1, 2). I-bar clasps provided similar (*P*=.33 for maxillary arch and *P*=.15 for mandibular arch) retention force values on all teeth (3.6 ±0.9 to 4.8 ±1.3 N) (Supplemental Table 3). Fatigue cycling significantly decreased the retention forces of wrought wire clasps on all teeth except incisors and of circumferential clasps on mandibular premolars and molars but did not affect the retention of I-bar clasps (Table 3).

Based on the data collected, an algorithm for predicting RPD retention was generated:

$$\text{RPD retention force} = \sum \text{clasp retention force} - \left(\text{Ka Kb Kc} \sum \text{disloding force on replaced tooth}\right), \quad \text{(Equation 2)}$$

where Ka is a constant for tooth surface anatomy, Kb is a constant for occlusion type, and Kc is a constant for food type (Supplemental Table 4).

A working version of the algorithm has been made available online at www.ebhnow.com/apps/0160. The deviation of this equation was ±8.1 N. The algorithm was validated experimentally on 36 randomly selected RPDs (Table 4). A total of 24 RPDs were predicted by the algorithm to provide sufficient retention and presented sufficient retention during the experimental retention test. In addition, 11 of 12 RPDs were predicted to provide insufficient retention and presented insufficient retention experimentally. Only 1 of 36 RPDs tested did not follow the prediction. Accordingly, the algorithm had a

Table 3. Retention forces of wrought wire and circumferential and I-bar clasps engaging on abutment teeth before and after fatigue

		Retention Forces (N) of					
		Wrought Wire Clasps		Circumferential Clasps		I-bar Clasps	
Arch	Tooth	1 Cycle	1200 Cycles	1 Cycle	1200 Cycles	1 Cycle	1200 Cycles
Maxillary	Central	9.3 ±1.1	9.1 ±1.1	3.4 ±0.8	2.9 ±1.2	4.2 ±1.7	3.9 ±1.2
	Lateral	8.7 ±1.9	8.5 ±1.6	4.1 ±0.7	3.4 ±1.5	4.0 ±1.2	3.6 ±0.9
	Canine	15.8 ±2.2	13.3 ±2.1*f	4.5 ±1.0	4.1 ±1.6	4.3 ±1.3	4.2 ±0.8
	First premolar	13.7 ±1.9	11.3 ±1.8*a	4.6 ±1.1	4.4 ±1.5	5.3 ±1.4	4.8 ±0.7
	Second premolar	13.8 ±3.0	10.7 ±2.1*e	5.3 ±1.2	4.5 ±1.1	5.2 ±1.3	4.8 ±1.2
	First molar	14.4 ±2.4	13.1 ±0.7 *d	6.9 ±0.7	6.8 ±1.0	5.0 ±0.5	4.8 ±1.3
	Second molar	14.2 ±2.7	13.1 ±1.5*h	6.8 ±1.0	6.1 ±0.9	5.0 ±0.4	4.7 ±0.9
Mandibular	Central	11.4 ±1.7	11.0 ±1.2	3.7 ±0.8	3.0 ±1.4	4.9 ±1.8	3.6 ±0.7
	Lateral	9.8 ±2.7	9.5 ±1.6	3.8 ±1.0	3.4 ±1.5	4.9 ±1.9	3.6 ±0.7
	Canine	15.9 ±2.4	14.0 ±1.7*a	5.2 ±2.2	4.3 ±1.0	4.8 ±2.2	4.3 ±0.9
	First premolar	13.3 ±1.2	12.2 ±1.2*c	6.3 ±0.8	5.0 ±0.8*e	5.1 ±1.4	4.8 ±0.5
	Second premolar	13.3 ±1.7	11.9 ±1.4*a	6.5 ±0.9	5.1 ±0.6*h	4.7 ±1.3	4.5 ±0.3
	First molar	18.3 ±3.0	14.5 ±1.7*a	7.2 ±1.0	6.2 ±0.9*h	4.6 ±0.5	4.5 ±0.6
	Second molar	17.3 ±3.2	13.6 ±2.6*b	7.2 ±0.7	6.2 ±1.0*g	5.1 ±0.9	4.6 ±1.4

*Significant difference between the retention forces of 1 cycle and 1200 cycles; *P*: a<.001, b=.002, c=.003, d=.008, e=.01, f=.02, g=.03, h=.04.

sensitivity of 96%, a specificity of 100%, and an accuracy of 97%.

DISCUSSION

The hypothesis of this study was confirmed. For an RPD to withstand mastication without being dislodged, the sum of the retention forces provided by each clasp should be higher than the sum of the dislodging forces generated by food mastication on each replaced missing tooth. By confirming the hypothesis, this study established a new approach for predicting and optimizing RPD retention using experimental data of forces produced by food and clasps during mastication (Equation 2). The authors are unaware of a previous engineering model that predicts the retention of any RPD. This could help dental professionals better determine the appropriate number and positions of clasps in RPDs and subsequent automatization of the designing process. Accordingly, the model developed in this study has the potential to enhance the quality of life for millions of patients worldwide by providing them with more predictable treatments.[7,25]

This study indicated that the forces exerted by food mastication depended on the tooth, occlusion, and food (Tables 1, 2). First, each tooth type and tooth anatomy generated a specific dislodging force. As reported previously,[13] the larger surface areas of posterior or anatomic teeth provided higher forces than the smaller surface areas in anterior or nonanatomic teeth. Moreover, the type of occlusion also affected the dislodging forces generated by food mastication, which might be related to the contact area between maxillary and mandibular teeth during mastication.[26] In addition, among the different food types tested, caramel exerted the highest forces, followed by chewing gum, whereas bread provided the lowest forces. This was due to the variable in stickiness among the different food types as reported previously.[25] Therefore, the algorithm for predicting RPD retention (Equation 2) must take into account the unique characteristic of each tooth and has to be adjusted for constants related to tooth anatomy, occlusion type, and food type.

The retention forces provided by wrought wire and circumferential clasps varied according to tooth type and clasp length. Wrought wire and circumferential clasps on larger teeth such as molars presented higher retention forces than those on smaller teeth such as incisors. The friction surface area between the wrought wire or circumferential clasp and the tooth might be the reason for the higher retention force on large teeth despite having longer and more flexible clasps.[14,15] The retention forces of I-bar clasps did not vary substantially among teeth possibly because their retention surface area and friction are similar across the different tooth types. Thus, the algorithm must take into account the differences among types of tooth and clasp. In addition, wrought wire clasps in this study showed higher retention forces than circumferential and I-bars probably because they possessed different undercuts. The wrought wire clasps were placed at undercuts of 0.5 mm, whereas circumferential and I-bar clasps were placed at undercuts of 0.1 mm due to the path of insertion and removal of the testing specimens. Thus, the retention forces of circumferential and I-bar clasps engaged in deeper undercuts would be comparable to the retention of Co-Cr clasps reported in the literature.[2,14,32]

Clasps undergo repeated bending caused by mastication, insertion, and removal of the RPD and therefore are vulnerable to the loss of retention. The retention of clasps usually changes after wearing the RPD for some time[28]; thus, cyclic fatigue testing of clasps was also assessed in this study. The retention forces of all types of clasps decreased

Table 4. Experimental retention performances of random RPDs in comparison with retention performances predicted by algorithm for predicting RPD retention

					Algorithm Prediction		Experimental Test
	Arch	Random Number	Edentulism Number	Clasps Position	Net force (N)	Sufficient retention	Sufficient retention
1	Mandibular	11 389	10111110001101	01000001010010	0.7	Yes	Yes
2		11 389	10111110001101	01000001000010	−13.0	No	No
3		11 389	10111110001101	01000001000000	−27	No	No
4		109	10110110000000	01001000000001	15.0	Yes	Yes
5		109	10110110000000	01000000000001	1.5	Yes	Yes
6		109	10110110000000	01000000000000	−10.0	No	No
7		11 283	11001000001101	00110100010010	13.0	Yes	Yes
8		11 283	11001000001101	00110000010010	3.5	Yes	Yes
9		11 283	11001000001101	00110000000010	−10.0	No	Yes*
10		358	01100110100000	10010000010001	29.5	Yes	Yes
11		358	01100110100000	10010000000001	15.0	Yes	Yes
12		358	01100110100000	10000000000001	3.3	Yes	Yes
13		6669	10110000010110	01001000001001	21.3	Yes	Yes
14		6669	10110000010110	01001000000001	8.0	Yes	Yes
15		6669	10110000010110	00001000000001	−10.0	No	No
16		9096	00010001110001	10001000001010	21.3	Yes	Yes
17		9096	00010001110001	10000000001010	15.3	Yes	Yes
18		9096	00010001110001	10000000000010	−10.0	No	No
19	Maxillary	3988	00101001111100	01010100000010	15.0	Yes	Yes
20		3988	00101001111100	01010000000010	7.2	Yes	Yes
21		3988	00101001111100	00010000000010	−6.0	No	No
22		285	00000100011101	00001010100010	20.0	Yes	Yes
23		285	00000100011101	00001000100010	6.0	Yes	Yes
24		285	00000100011101	00001000000010	−1.6	No	No
25		5880	00011111011010	00100000100101	11.0	Yes	Yes
26		5880	00011111011010	00100000100001	−0.3	No	No
27		5880	00011111011010	00100000100001	−10.0	No	No
28		2770	01001011010100	10100000001010	16.8	Yes	Yes
29		2770	01001011010100	10000000001010	5.7	Yes	Yes
30		2770	01001011010100	10000000001000	−7.0	No	No
31		10 846	01111010010101	10000101101010	24.0	Yes	Yes
32		10 846	01111010010101	10000100101010	6.7	Yes	Yes
33		10 846	01111010010101	10000100101000	1.9	Yes	Yes
34		12 444	00111001000001	01000110100100	12.4	Yes	Yes
35		12 444	00111001000001	01000100100100	6.5	Yes	Yes
36		12 444	00111001000001	01000100000100	−4.2	No	No
True positive			24				
True negative			11				
False positive			0				
False negative			1				
Sensitivity			96%				
Specificity			100%				
Accuracy			97%				

RPD, removable partial denture. Sufficient retention ability to resist dislodging forces caused during food mastication. *Indicates difference between predicted and tested RPD retention.

after cyclic fatigue, which could be due to clasp deformation on the wear between the crown and the inner surface of the clasp.[14,29] This can decrease the friction coefficient between the clasp and the abutment tooth and lead to loss of retention.[32] The loss of retention was more pronounced on long wrought wire clasps than on short ones, which agrees with a previous study.[17] Surprisingly, even though wrought wire clasps are known to maintain much of their retention after cyclic testing because of their flexibility, both I-bar and circumferential clasps in this study outperformed the wrought wire clasps.[30] This is probably because the I-bar and circumferential clasps were prepared by laser-sintering technology and were engaging smaller undercuts.[20]

The algorithm for predicting RPD retention was validated experimentally in a blinded test to avoid bias. Only 1 of 36 RPDs tested did not follow the prediction; this RPD showed higher experimental retention than predicted, which might be related to the friction of the clasps. Accordingly, the sensitivity of the algorithm was 96%, and the specificity was 100%; this means that all the RPDs predicted to have sufficient retention by the algorithm presented sufficient retention during food mastication, whereas 96% of the RPDs that are predicted to have insufficient retention presented insufficient retention during food mastication. Generally, the algorithm for predicting RPD retention was confirmed with an accuracy of 97%.

Limitations of this study should be considered in future studies to improve the clinical performance of the algorithm. For example, parameters that may vary among patients were not tested. This includes tooth anatomy, height of tooth crown, mastication mechanics (such as mastication speed, angle, and food volume), and the path of insertion and removal of the RPDs.[13] Another limitation was that the clasp retention experiments were performed in a dry ambient condition with acrylic resin teeth; this might underestimate clasp retention force in the oral environment because of the adhesive effect of saliva in tooth-clasp interactions.[18,33] In addition, variations in the fabrication process of RPDs (such as clasps materials, thickness, length, and undercut depth) between dental clinics and laboratories might limit the validity of the algorithm in clinical practices.[14,18] Moreover, other clasp types and retentive features of RPDs such as rotational partial dentures were not addressed in this algorithm; including these permutations would acknowledge deviations in the algorithm.[16,19,34] Nevertheless, with the arrival of computer-aided design and computer-aided manufacturing (CAD-CAM) technology and the digitalization of the RPD fabrication process, these limitations can be overcome.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The force generated by food mastication on teeth varied according to the type of tooth, occlusion, and food.
2. The retention force of RPD clasps varied according to the type of tooth and clasp.
3. An algorithm for predicting RPD retention and determining the optimal number of clasps was developed and validated experimentally.

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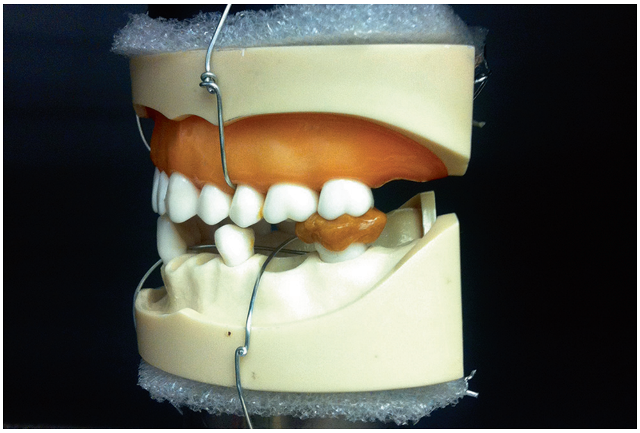
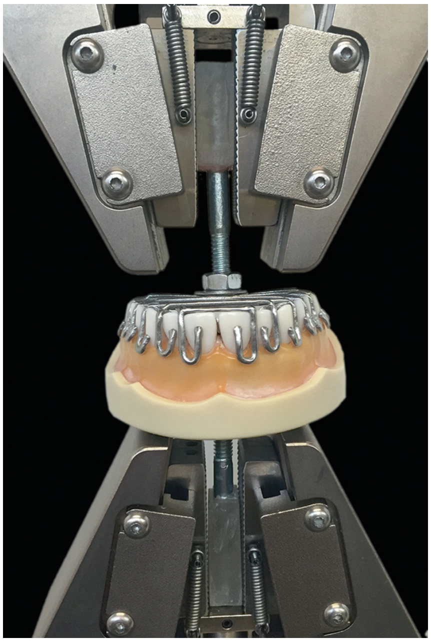


Supplemental Figure 1. Experimental design for measuring forces exerted by food on acrylic resin teeth.

Supplemental Figure 2. Experimental design for measuring retention force of circumferential clasps engaging on teeth.



Supplemental Figure 3. Experimental design for measuring retention force of I-bar clasps engaging on teeth.

Supplemental Table 1. Retention forces of wrought wire clasps after fatigue for post hoc comparison between tooth types

Arch	Tooth	Retention Forces (N) of Wrought wire clasp	*P* Values for Post hoc Comparison Between Tooth Type: Central	Lateral	Canine	First premolar	Second premolar	First molar	Second molar
Maxillary	Central	9.1 ±1.1	–	.824	<.001	.003	.086	<.001	<.001
	Lateral	8.5 ±1.6	.824	–	<.001	<.001	<.001	<.001	<.001
	Canine	13.3 ±2.1	<.001	<.001	–	<.001	<.001	1.0	1.0
	First premolar	11.3 ±1.8	.003	<.001	.006	–	.942	.013	.019
	Second premolar	10.7 ±2.1	.086	.001	<.001	.945	–	<.001	<.001
	First molar	13.1 ±0.7	<.001	<.001	1.0	.013	<.001	–	1.0
	Second molar	13.1 ±1.5	<.001	<.001	1.0	.019	<.001	1.0	–
Mandibular	Central	11.0 ±1.2	–	.172	<.001	.117	.433	<.001	<.001
	Lateral	9.5 ±1.6	.172	–	<.001	<.001	<.001	<.001	<.001
	Canine	14.0 ±1.7	<.001	<.001	–	<.001	<.001	.926	.988
	First premolar	12.2 ±1.2	.117	<.001	<.001	–	.994	<.001	.015
	Second premolar	11.9 ±1.4	.433	<.001	<.001	.994	–	<.001	<.001
	First molar	14.5 ±1.7	<.001	<.001	.926	<.001	<.001	–	.503
	Second molar	13.6 ±2.6	<.001	<.001	.988	.015	<.001	.50	–

Supplemental Table 2. Retention forces of circumferential clasps after fatigue for post hoc comparison between tooth types

Arch	Tooth	Retention Forces (N) of circumferential clasp	*P* Values for Post hoc Comparison Between Tooth Types: Central	Lateral	Canine	First premolar	Second premolar	First molar	Second molar
Maxillary	Central	2.9 ±1.2	–	.998	.752	.526	.450	.001	.008
	Lateral	3.4 ±1.5	.998	–	.963	.842	.780	.004	.031
	Canine	4.1 ±1.6	.752	.963	–	1.0	1.0	.041	.217
	First premolar	4.4 ±1.5	.526	.842	1.0	–	1.0	.092	.393
	Second premolar	4.5 ±1.1	.450	.780	1.0	1.0	–	.118	.465
	First molar	6.8 ±1.0	.001	.004	.041	092	.118	–	.981
	Second molar	6.1 ±0.9	.008	.031	.217	.393	.465	.981	–
Mandibular	Central	3.0 ±1.4	–	.997	.562	.138	.099	.003	.003
	Lateral	3.4 ±1.5	.997	–	.879	.369	.283	.011	.014
	Canine	4.3 ±1.0	.562	.879	–	.970	.934	.170	.197
	First premolar	5.0 ±0.8	.138	.369	.970	–	1.0	.631	.681
	Second premolar	5.1 ±0.6	.099	.283	.934	1.0	–	.729	.775
	First molar	6.2 ±0.9	.003	.011	.170	.631	.729	–	1.0
	Second molar	6.2 ±1.0	.003	.014	.197	.681	.775	1.0	–

Supplemental Table 3. Retention forces of I-bar clasps after fatigue for post hoc comparison between tooth types

Arch	Tooth	Retention Forces (N) of I-bar clasp	*P* Values for Post hoc Comparison Between Tooth Types						
			Central	Lateral	Canine	First premolar	Second premolar	First molar	Second molar
Maxillary	Central	2.9 ±1.2	—	.999	1.0	.834	.770	.803	.862
	Lateral	3.4 ±1.5	.999	—	.979	.584	.507	.546	.623
	Canine	4.1 ±1.6	1.0	.979	—	.965	.937	.953	.975
	First premolar	4.4 ±1.5	.834	.584	.965	—	1.0	1.0	1.0
	Second premolar	4.5 ±1.1	.770	.507	.937	1.0	—	.118	.465
	First molar	6.8 ±1.0	.803	.546	.953	1.0	1.0	—	1.0
	Second molar	6.1 ±0.9	.862	.623	.975	1.0	1.0	1.0	—
Mandibular	Central	3.0 ±1.4	—	1.0	.806	.265	.647	.659	.548
	Lateral	3.4 ±1.5	1.0	—	.741	.216	.572	.585	.475
	Canine	4.3 ±1.0	.806	.741	—	.961	1.0	1.0	.999
	First premolar	5.0 ±0.8	.265	.216	.961	—	.993	.992	.998
	Second premolar	5.1 ±0.6	.647	.572	1.0	.993	—	1.0	1.0
	First molar	6.2 ±0.9	.659	.585	1.0	.992	1.0	—	1.0
	Second molar	6.2 ±1.0	.548	.475	.999	.998	1.0	1.0	—

Supplemental Table 4. Constant factor in algorithm for predicting RPD retention, equation 2, for mastication of different types of food on different tooth anatomy and occlusion

Constant	Condition	Maxillary Arch	Mandibular Arch
Ka: Constant for tooth anatomy	Anatomical teeth	1.0	1.0
	Nonanatomical teeth	0.89	0.91
Kb: Constant for occlusion type	Class 1 occlusion	1.0	1.0
	Class 2 occlusion	0.96	0.81
	Class 3 occlusion	0.91	0.83
Kc: Constant for food type	Caramel candy	1.0	1.0
	Chewing gum	0.32	0.31
	Bread	0.12	0.12

RPD, removable partial denture.