

## Mechanical analysis of factors affecting clear aligner removability

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It is difficult to control corrective forces in orthodontic treatment with clear aligners. The grip of aligners on teeth is important to ensure accurate corrective forces from aligners. This study aimed to measure the gripping force of aligners under various conditions to clarify factors that influence it. We created aligners with different attachment morphologies and placement sites and different margin lengths. We developed a device to measure the mechanics involved in the removal of these aligners. The gripping force was evaluated at five different aligner removal sites on the teeth. We found that the gripping force of the aligner was the weakest on the lingual side of the first molar and strongest on the labial side of the central incisors and that the attachment morphology and placement sites affected the gripping force of aligners.

**Keywords:** Clear aligners, Gripping force, Attachment shapes, Aligner margin, Attachment position

### INTRODUCTION

Several previous studies have reported regarding the treatment effects of clear aligners, particularly with respect to tooth movement<sup>1-7</sup>. Aligner treatment is considered the least accurate strategy for orthodontic tooth movements such as extrusion and mesiodistal inclination<sup>8</sup>. Djeu *et al.* stated that although aligners have the advantages of being esthetically appealing, removable, and comfortable, they lack the biomechanical advantages of fixed appliances<sup>9</sup>. As shown in previous studies, compared with the fixed appliance treatment, aligner treatment may be unreliable in enabling precise tooth movements. Therefore, to better control orthodontic tooth movement during aligner treatment, placement of attachments (elevations prepared on tooth surfaces) has been recommended to strengthen the gripping force of aligners. Furthermore, attachments can make aligners rotate the teeth more effectively<sup>10</sup>. Goto *et al.* stated that attachments increase the area of contact between the aligner and teeth, which may enable aligners to correct teeth more effectively<sup>11</sup>. Another report suggested that aligner retention is stronger with rectangular attachments than with beveled trapezoidal attachments and that attachments provided greater aligner retention when placed closer to the gingiva<sup>12</sup>. Furthermore, other studies indicated that thicker aligner materials led to increased aligner retention and that longer aligner margins provided greater aligner retention<sup>13,14</sup>. However, no previous study has assessed the gripping force of aligners under various conditions according to aligner removal sites. Increasing the number of attachments can make aligner removal difficult, rendering it less user-friendly, which in turn may affect the duration of wearing aligners by patients. In this study, we hypothesized that the morphology and placement site of aligner attachments and the aligner margin trim line

would affect the gripping force of aligners and that the force required for the removal of aligners would differ depending on the removal site.

Furthermore, a study assessed the limitations of orthodontic treatment using aligners alone, including reports on the efficacy of a combination technique that incorporates the use of aligners together with a fixed appliance<sup>4</sup>. Moreover, another study suggests that this combination technique can shorten the duration of treatments and reduce the burden on roots and periodontal tissues compared with aligner treatment alone<sup>15</sup>.

Thus, this study aimed to evaluate the effects of attachment morphology and placement site, aligner margin trim line, and differences in sites on which forces act during aligner removal on the gripping force of aligners. Furthermore, we examined the possibility of using orthodontic brackets as attachments for aligners. By identifying factors that improve the grip of aligners, we hope to provide orthodontists with information on designing more comfortable aligners for patients.

### MATERIALS AND METHODS

Optical impressions of maxillary dental models (No. E-54, Nissin, Kyoto, Japan) were created using Trios Pod (3Shape TRIOS Intraoral Scanner, 3Shape, Copenhagen, Denmark), and stereolithography (STL) data were created. Next, a computer-aided design (CAD) software (Geomagic Freeform Touch X, 3D SYSTEMS, Rock Hill, SC, USA) was used to place attachments on the tooth surfaces of the STL dental model. A base plate for fixing the models to the measurement device was also created using the CAD software (Fig. 1).

Eleven types of attachments were used in this study and were placed on the centers of the crowns on the STL dental model, as described below (Fig. 2, Table 1). Model

No. 0 was defined as control (without attachment). For Nos. 1–3, the attachment morphology on the cervical side of the teeth was modified by overlaying triangular prisms of different gradients on the STL model of zirconia ceramic brackets (MANEWVER®, GC ORTHOLY, Tokyo, Japan), which are commercially available forms of non-ligating brackets (Fig. 3). Nos. 4–6 were rectangular attachments with differences only in the major axis lengths. No. 7 was of the same shape as attachment No. 6 but with a different thickness. Nos. 8 and 9 were ellipsoid attachments of different sizes. For Nos. 10 and 11, two different-sized semi-elliptical attachments were placed on the crown of a single tooth. All attachments were placed either on the maxillary lateral incisors or the maxillary first premolars (Fig. 4).

The maxillary lateral incisors have the lowest accuracy for intrusion<sup>9)</sup>, while the maxillary first premolars have the lowest accuracy for rotational movement<sup>16)</sup>. These are frequently used sites of attachment placement in clinical practice. The data for the 23 models (No. 0, 11 maxillary lateral incisor attachment forms, and 11 maxillary first premolar

attachment forms) were printed using a three-dimensional printer (AGILISTA-3200, Keyence, Osaka, Japan) to prepare measurement models, which were made of clear resin. The models were also printed without foundations on them, and these models were used as molds for the aligners. The aligners were fabricated using polyethylene terephthalate-glycol copolyester

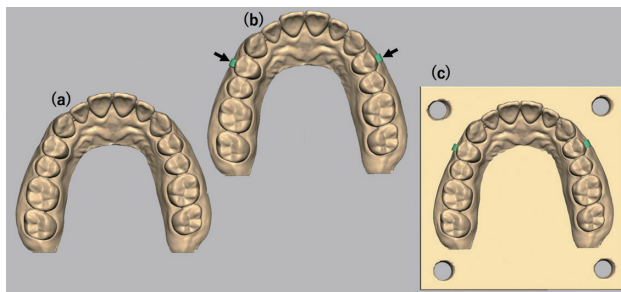


Fig. 1 Maxillary dental model data. (a) STL dental model, (b) Attachments placed on the left and right maxillary first premolars, (c) With base plate for fixation (length×width×thickness: 75.0×75.0×4.0 mm) on the basal surface of the STL dental model.

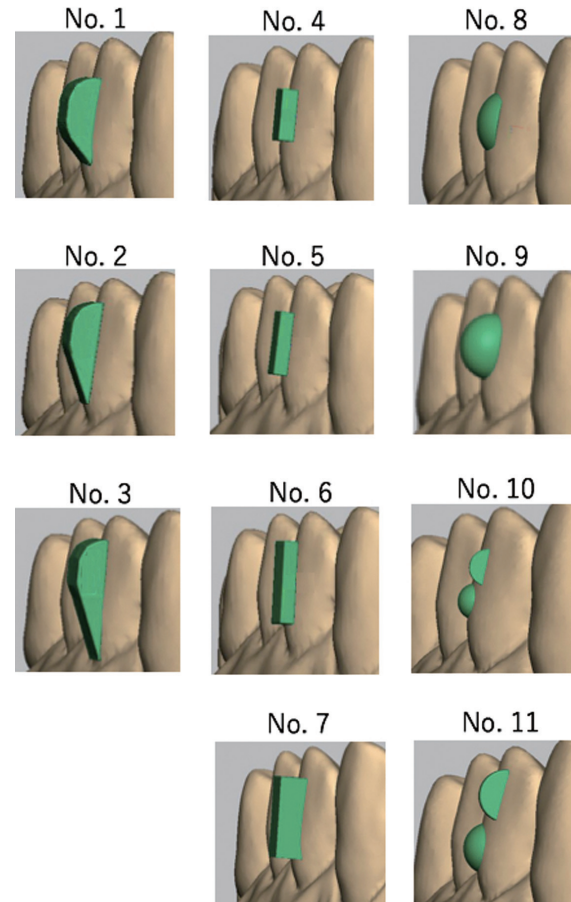


Fig. 2 Attachment shapes.

Table 1 Attachment type

No.	Shapes	Height×width×depth (mm)	Pieces for a tooth
0	No attachment		0
1	MANEWVER	5.0×2.5×1.5	1
2		6.0×2.5×1.5	1
3		7.0×2.5×1.5	1
4	Rectangular shape	3.0×2.0×1.0	1
5		4.0×2.0×1.0	1
6		5.0×2.0×1.0	1
7		5.0×2.0×1.0	1
8	Elliptical shape	3.0×2.0×1.0	1
9		4.0×3.0×2.0	1
10	Half-Elliptical shape	1.0×2.0×1.0	2
11		2.0×3.0×2.0	2

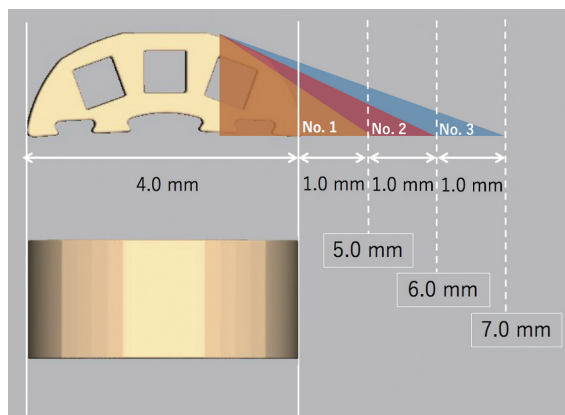


Fig. 3 Detailed dimensions of attachment Nos. 1–3.

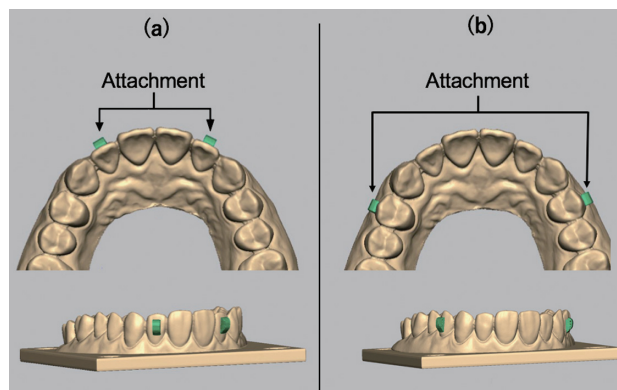


Fig. 4 Attachments placed on the maxillary lateral incisors (a) or first premolars (b).

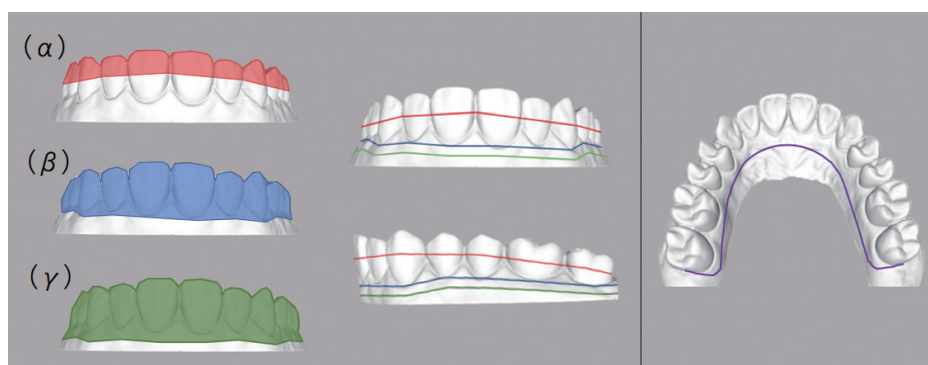


Fig. 5 Aligner margin lengths.

( $\alpha$ ) Red: center height of the crown; ( $\beta$ ) blue: gingival zenith; ( $\gamma$ ) green: 2.0 mm below the gingival zenith ( $\alpha$ ,  $\beta$ ,  $\gamma$  common). Purple line: the aligner is trimmed 3.0 mm from the gingival zenith.

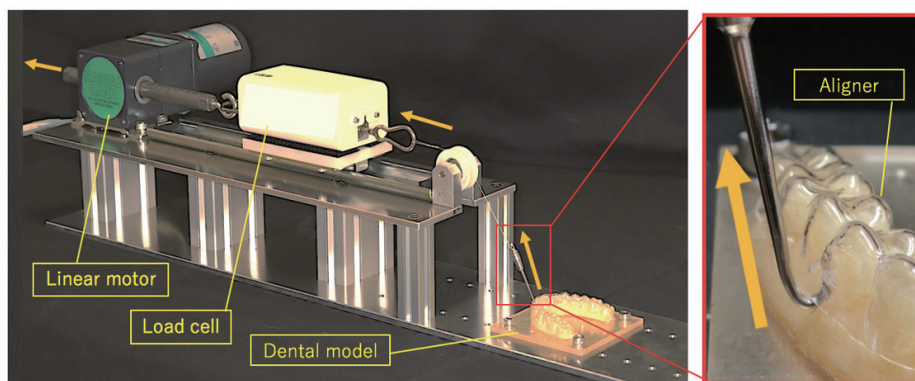


Fig. 6 Device for measuring the force necessary to remove the aligner.

0.6-mm sheets (Erkodur, Erkodent, Pfalzgrafenweiler, Germany) on the thermoforming machine (Erkpress ci motion, Erkodent). According to Erkodur's official product datasheet<sup>17)</sup>, the physical properties of the sheet material are tensile strength, 53 MPa (ISO 527); flexional strength, 69 MPa (IOS 178); yield stress, 53 MPa (ISO 527); and Rockwell hardness, 115 MPa (D

785).

For model No. 0 (without attachments), we prepared three aligners that differed in their buccal margin form in the vertical direction. The margins of these aligners were trimmed either along the center of the crown ( $\alpha$ ), the gingival zenith ( $\beta$ ), or 2.0 mm from the gingival zenith ( $\gamma$ ) (Fig. 5). For model Nos. 1–11, the aligner margin on

the buccal side was trimmed in a straight line along the gingival zenith. The lingual margin for model Nos. 0–11 was uniformly trimmed in a straight line 3.0 mm from the gingival zenith.

For measurement, we manufactured a device that could pull model-mounted aligners at a constant speed (Fig. 6). The model was fixed to the device using screws, and the aligner was placed on the model. A load cell with wheels was placed on a rail, and an aligner lifter (Forestadent, Iserlohn, Germany) (an assistive device that hitches a hooked tip onto the edge of an aligner to pull it) was attached with a 0.1-mm wire to the front of the load cell to pull the aligner. By conducting measurements upon removal of the aligner from its margin using the aligner lifter, we recreated the actual removal of an aligner with a fingernail or finger. Furthermore, by removing the aligner from the cervical margin, we recreated the direction of force used upon actual removal of an aligner from the mouth. A pulley was used to reduce the wire friction during pulling. A linear motor was connected to the back of the load cell to

pull the aligner at a rate of 1.5 mm/s. The measurements were calculated using an Arduino calculator and recorded 10 times per second during pulling to determine the maximum force required to remove the aligner.

The aligners were pulled from five different sites: the labial side between the maxillary central incisors (labial side of 1), labial and lingual sides of the right maxillary first premolar (labial and lingual sides of 4), and labial and lingual sides of the right maxillary first molar (labial and lingual sides of 6) (Fig. 7). Three aligners were prepared for each model, and three measurements were performed at each of the five points. Then, the mean of the nine maximum measurement values was calculated.

Intraclass correlation coefficient (ICC) was calculated to evaluate the reliability of the measured data within the same model. The normality of the data was confirmed using the Shapiro-Wilks’s test. Although the data contained both normal and non-normal distributions, a two-way analysis of variance (ANOVA) was performed assuming a normal distribution, since this was a small-

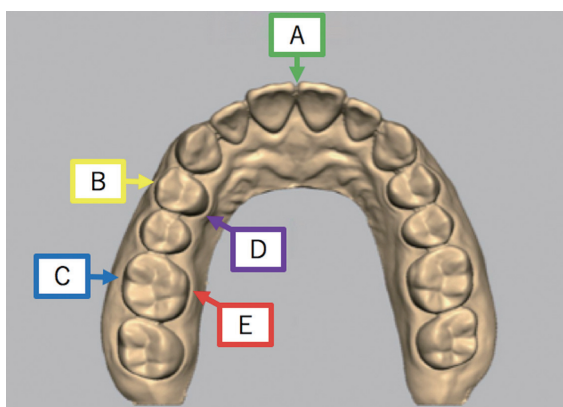


Fig. 7 Application points of the removal force. A: Labial side of maxillary central incisors; B: Labial side of right maxillary first premolar; C: Labial side of right maxillary first molar; D: Lingual side of right maxillary first premolar; and E: Lingual side of right maxillary first molar.

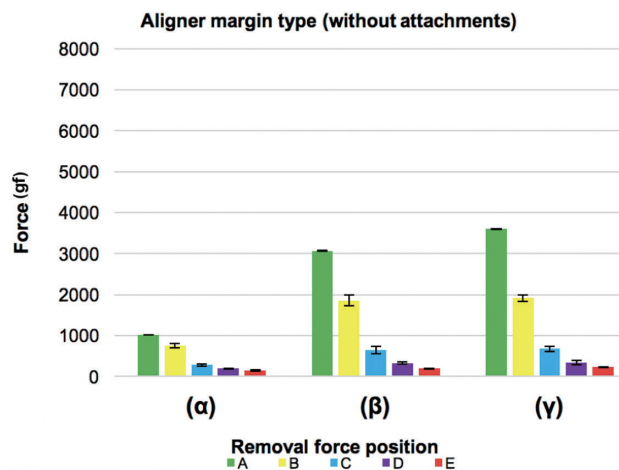


Fig. 8 Average maximum force according to the length of the aligner margin without attachments (See Fig. 5).

Table 2 Results of two-way ANOVA

		Type III sum of squares	df	Mean square	F value	p value
Factors	Sites of aligner removal force action	1,908,689,591	4	477,172,398	3,605.474	<0.001*
	Aligner conditions (Margin type, Attachment forms, Attachment placement site)	126,404,461	24	5,266,853	39.796	<0.001*
	Interaction	181,094,072	96	1,886,397	14.253	<0.001*
	Statistical error	132,346,647	1,000	132,347	—	—

\*Significant difference,  $p < 0.05$ .

scale analysis. The equality of variance of the data was confirmed using the Levene test.

A two-way ANOVA was used to analyze

measurements, and the Games-Howell method was used as a *post-hoc* test. Statistical analysis was performed to determine whether there were any significant differences

Table 3 Maximum force averages according to the aligner margin lengths without attachments. [gf]

		Sites of aligner removal force action				
		A	B	C	D	E
Margin type	$\alpha$	1,018 (100)	755 (72)	282 (44)	193 (40)	148 (19)
	$\beta$	3,065 (202)	1,858 (157)	653 (105)	333 (35)	196 (30)
	$\gamma$	3,599 (297)	1,915 (170)	674 (103)	344 (75)	233 (19)

( ) : Standard deviation

Table 4 Comparison of aligner margin types using the Games-Howell *post-hoc* test.

		Sites of aligner removal force action				
		A	B	C	D	E
Margin type		<i>p</i> value				
( $\alpha$ )-( $\beta$ )		<0.001*	<0.001*	<0.001*	<0.001*	0.089
( $\alpha$ )-( $\gamma$ )		<0.001*	<0.001*	0.000*	0.017*	<0.001*
( $\beta$ )-( $\gamma$ )		0.047*	0.999	0.999	0.999	0.402

\*Significant difference, *p*<0.05.

Table 5 Comparison of aligner removal sites by aligner margin type using the Games-Howell *post-hoc* test.

Margin type	Sites of aligner removal force action	<i>p</i> value	Margin type	Sites of aligner removal force action	<i>p</i> value	Margin type	Sites of aligner removal force action	<i>p</i> value
	A	B <0.001*		A	B <0.001*		A	B <0.001*
		C <0.001*			C <0.001*			C <0.001*
		D <0.001*			D <0.001*			D <0.001*
		E <0.001*			E <0.001*			E <0.001*
	B	A <0.001*		B	A <0.001*		B	A <0.001*
		C <0.001*			C <0.001*			C <0.001*
		D <0.001*			D <0.001*			D <0.001*
		E <0.001*			E <0.001*			E <0.001*
$(\alpha)$	C	A <0.001*	$(\beta)$	C	A <0.001*	$(\gamma)$	C	A <0.001*
		B <0.001*			B <0.001*			B <0.001*
		D 0.003*			D <0.001*			D <0.001*
		E <0.001*			E <0.001*			E <0.001*
	D	A <0.001*		D	A <0.001*		D	A <0.001*
		B <0.001*			B <0.001*			B <0.001*
		C 0.003*			C <0.001*			C <0.001*
		E 0.062			E <0.001*			E 0.013*
	E	A <0.001*		E	A <0.001*		E	A <0.001*
		B <0.001*			B <0.001*			B <0.001*
		C <0.001*			C <0.001*			C <0.001*
		D 0.062			D <0.001*			D 0.013*

\*Significant difference, *p*<0.05.

among the groups, with the level of significance set at  $p < 0.05$ . IBM SPSS version 26.0 (IBM SPSS Japan, Tokyo, Japan) was used for statistical analyses.

In this study, we examined the following two factors:

1. Differences among the five aligner removal sites (A, B, C, D, and E)
2. Aligner conditions, including the length of the aligner margins ( $\alpha$ ,  $\beta$ , and  $\gamma$ ), differences among the 11 types of attachment forms (Nos. 1-11), and differences between the attachment placement sites (maxillary lateral incisors and maxillary first premolars)

### RESULTS

The ICCs were 0.950 for the labial side of 1; 0.951 and 0.942 for the labial and lingual sides of 4, respectively; and 0.981 and 0.969 for the labial and lingual sides of 6, respectively.

The results of two-way ANOVA showed that there was a significant difference between the removal site and the aligner condition (both  $p < 0.05$ ). Moreover, there was a significant interaction between these factors ( $p < 0.05$ , Table 2).

### Experiment 1: Comparison of different types of aligner margins

Figure 8 and Table 3 show the average maximum force

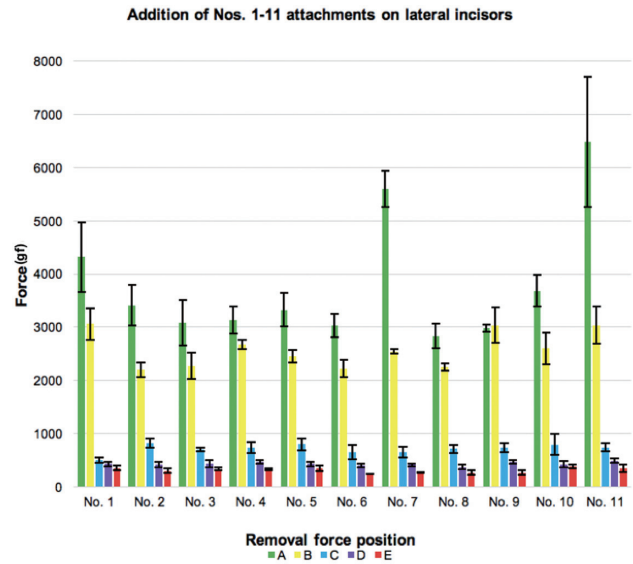


Fig. 9 Average maximum force after placing attachments Nos. 1-11 on the lateral incisors.

Table 6 Maximum force averages for addition of attachments Nos. 1-11 on the lateral incisors as compared to the control (without attachment) using the Games-Howell *post-hoc* test. [gf]

	Sites of aligner removal force action										
	A		B		C		D		E		
	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	
Control (without attachment)	3,065 (202)	—	1,858 (157)	—	653 (105)	—	333 (35)	—	196 (30)	—	
Attachment forms	No.1	4,318 (1,118)	0.326	3,058 (336)	<0.001*	490 (57)	0.101	422 (66)	0.225	346 (45)	<0.001*
	No.2	3,407 (548)	0.959	2,192 (173)	0.056	825 (139)	0.438	409 (77)	0.606	302 (41)	0.003*
	No.3	3,086 (518)	1.000	2,273 (291)	0.159	700 (77)	0.999	431 (76)	0.251	336 (27)	<0.001*
	No.4	3,128 (310)	<0.001*	2,669 (107)	<0.001*	741 (143)	0.994	458 (54)	0.006*	332 (22)	<0.001*
	No.5	3,323 (414)	0.975	2,448 (223)	0.002*	796 (125)	0.619	425 (50)	0.045*	342 (56)	0.002*
	No.6	3,032 (407)	1.000	2,219 (193)	0.052	652 (186)	1.000	397 (97)	0.945	248 (13)	0.048*
	No.7	5,600 (896)	0.002*	2,543 (406)	0.051	655 (155)	1.000	406 (68)	0.522	267 (17)	0.004*
	No.8	2,831 (442)	0.994	2,247 (181)	0.019*	711 (115)	0.999	366 (52)	0.988	268 (45)	0.117
	No.9	2,982 (518)	1.000	3,031 (365)	<0.001*	736 (85)	0.955	463 (53)	0.004*	266 (48)	0.173
	No.10	3,685 (562)	0.385	2,605 (541)	0.145	790 (213)	0.968	414 (69)	0.373	376 (41)	<0.001*
	No.11	6,479 (1,872)	0.032*	3,037 (404)	0.001*	741 (165)	0.998	483 (90)	0.059	348 (72)	0.012*

\*Significant difference,  $p < 0.05$ .

( ): Standard deviation

applied for aligner removal according to different aligner margins without attachments. Among the five removal sites, the amount of force required to remove the aligner was the greatest with the aligner margin at 2.0 mm from the gingival zenith ( $\gamma$ ), followed by that at the gingival zenith ( $\beta$ ) and the center of the crown ( $\alpha$ ).

The Games-Howell *post-hoc* test showed that there was a statistically significant difference between the aligner margins at the center of the crown and the gingival zenith, except for the measurements of aligner removal from the lingual side of 6 (site E) (Table 4). There was a significant difference in the measurements of all removal sites between aligners with the margins at the center of the crown and at 2.0 mm from the gingival zenith. A statistically significant difference was observed between the gingival zenith cut and the 2.0-mm cut from the gingival zenith, only for aligner removal from the labial side of 1 (A). The results indicated that the longer the aligner margin, the greater the gripping force and that the length of the aligner margin could be increased to 2.0 mm in the anterior teeth to increase the gripping force. In addition, during the removal of aligners with varying marginal morphology, there was a significant difference in gripping force among all removal sites ( $p < 0.05$ ), except between the lingual side of 4 (site D) and that of 6 (Table 5). Specifically, regardless of the margin design, the gripping force tended to weaken in the order of A→B→C→D→E.

*Experiment 2: Comparison of attachments Nos. 1–11 placed on the bilateral maxillary lateral incisors*

Figure 9 and Table 6 show the comparison of the average maximum force used to remove the aligner according to the removal site and attachment type when the attachments were placed on maxillary lateral incisors.

Comparison with the control (without attachment) using the Games-Howell *post-hoc* test showed that the attachment types No. 7 and No. 11 were significantly different from the control in terms of the removal force of the aligner from the labial side of 1 (site A). On removal of the aligner from the labial side of 4 (site B), there was a significant difference in the removal force values for attachments Nos. 1, 4, 5, 8, 9, and 11 from that of the control. Aligner removal from the labial side of 6 (C) showed no significant difference from the control in the measured removal force values for all attachments.

In terms of the removal force of the aligner from the lingual side of right maxillary first premolar for attachments Nos. 4, 5, and 9, there was a significant difference in the values from that of the control. In the case of aligner removal from the lingual side of 6 (E), significant differences were observed in the removal force values measured for attachments other than the ellipsoid attachments Nos. 8 and 9 compared with the control. Thus, the attachment on the lateral incisor was shown to play a role in increasing the grip of the aligner at each site. However, the attachment on the lateral incisor may not contribute to the gripping force of the aligner on the labial side of 6 (C).

Table 7 shows the comparison of the same types of attachments, *i.e.*, among Nos. 1–3, in which different inclination angles of MANEVR were used; among Nos. 4–6, in which the length of the rectangle differed; between No. 6 and No. 7, in which the thickness of the rectangle differed; between No. 8 and No. 9, in which the thickness and diameter of the ellipsoid attachment size differed; and between No. 10 and No. 11, in which the thickness and diameter of the semicircular attachment differed. There was a significant difference in the values measured between attachments No. 1 and No. 2 and

Table 7 Comparison of attachments between similar forms using the Games-Howell *post-hoc* test (attachment placed on the lateral incisor).

Attachment placement site	Attachment forms	Sites of aligner removal force action				
		A	B	C	D	E
Lateral incisors	No.1–No.2	0.827	0.002*	0.004*	1.000	0.846
	No.2–No.3	0.999	1.000	0.757	1.000	0.891
	No.1–No.3	0.424	0.010*	0.001*	1.000	1.000
	No.4–No.5	0.294	0.568	1.000	0.998	1.000
	No.5–No.6	0.994	0.775	0.932	0.017*	0.051
	No.4–No.6	0.286	0.005*	1.000	0.979	<0.001*
	No.6–No.7	0.001*	0.839	1.000	1.000	0.584
	No.8–No.9	1.000	0.009*	1.000	0.110	1.000
	No.10–No.11	0.098	1.000	1.000	0.962	1.000

\*Significant difference,  $p < 0.05$ .

between No. 1 and No. 3 for aligner removal on the labial side of 4 (B) and the labial side of 6 (C), which suggested that the gripping force of the aligner became

smaller when the inclination angle of the edge of the MANEWVER was reduced. There was a significant difference between the measurements of attachments No. 4 and No. 6 for removal of the aligner from the labial side of the right maxillary first premolar (B) and the lingual side of 6 (E), suggesting that the gripping force of the aligner increased with the increase in the diameter of the rectangular attachment. There was a significant difference between attachments No. 6 and No. 7 in the removal of the aligner from the labial side of 1 (A), suggesting that the gripping force of the aligner increased with increasing thickness of the rectangular attachment. There was a significant difference between attachments No. 8 and No. 9 in the removal of aligners from the buccal side of the labial side of 4 (B), suggesting that by increasing the thickness and diameter of the ellipsoid attachment, the gripping force of the aligners was increased.

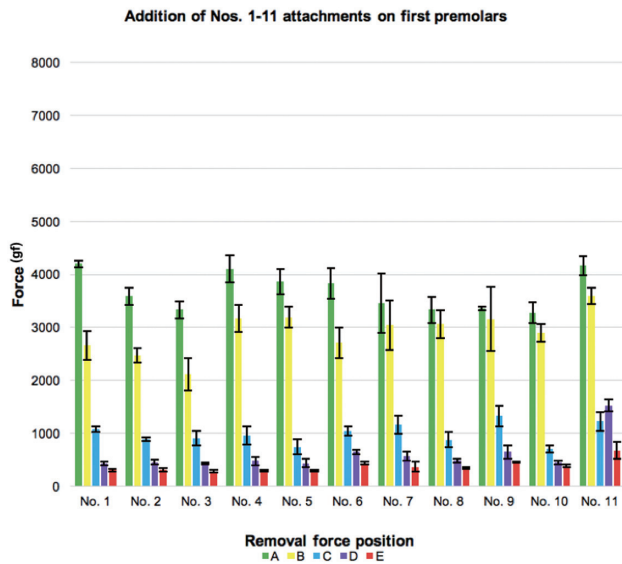


Fig. 10 Average maximum force after placing attachments Nos. 1-11 on the first premolars.

Experiment 3: Comparison of attachments Nos. 1-11 on the bilateral maxillary first premolars

Figure 10 and Table 8 show the comparisons of the average maximum force used for aligner removal according to the removal site and attachment type when the attachments were placed on the maxillary first premolars. The Games-Howell test revealed that

Table 8 Maximum force averages for the addition of attachments Nos. 1-11 on the first premolar as compared to the control (without attachment) using the Games-Howell *post-hoc* test. [gf]

		Sites of aligner removal force action									
		A		B		C		D		E	
		Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value	Maximum force averages	<i>p</i> value
Control (without attachment)		3,065 (202)	—	1,858 (157)	—	653 (105)	—	333 (35)	—	196 (30)	—
Attachment forms	No.1	4,196 (205)	<0.001*	2,657 (343)	0.005*	1,071 (146)	<0.001*	434 (48)	0.019*	306 (48)	0.007*
	No.2	3,585 (332)	0.105	2,469 (517)	0.287	890 (82)	<0.001*	453 (47)	0.003*	310 (40)	0.001*
	No.3	3,330 (326)	0.883	2,112 (404)	0.960	904 (175)	0.173	424 (20)	0.002*	278 (38)	0.016*
	No.4	4,107 (466)	0.007*	3,163 (378)	<0.001*	961 (206)	0.119	476 (88)	0.066	289 (23)	<0.001*
	No.5	3,865 (594)	0.169	3,187 (335)	<0.001*	744 (190)	0.999	438 (109)	0.560	287 (37)	0.005*
	No.6	3,835 (560)	0.156	2,707 (439)	0.021*	1,038 (96)	<0.001*	647 (82)	<0.001*	435 (27)	<0.001*
	No.7	3,451 (780)	0.993	3,041 (1,036)	0.303	1,163 (324)	0.075	560 (149)	0.088	368 (104)	0.058
	No.8	3,328 (347)	0.916	3,060 (384)	<0.001*	879 (200)	0.421	482 (52)	0.001*	348 (21)	<0.001*
	No.9	3,354 (682)	0.999	3,154 (809)	0.066	1,322 (253)	0.002*	643 (183)	0.048*	456 (28)	<0.001*
	No.10	3,276 (459)	0.999	2,893 (267)	<0.001*	698 (114)	1.000	441 (44)	0.005*	387 (28)	<0.001*
	No.11	4,164 (921)	0.264	3,599 (672)	0.003*	1,222 (196)	0.001*	1,519 (363)	0.001*	671 (181)	0.003*

\*Significant difference, *p*<0.05.  
( ) : Standard deviation

Table 9 Comparison of attachments between similar forms using the Games-Howell method (attachment placed on the first premolar).

Attachment placement site	Attachment forms	Sites of aligner removal force action				
		A	B	C	D	E
First premolars	No.1–No.2	0.927	1.000	0.317	1.000	1.000
	No.2–No.3	1.000	0.985	1.000	0.972*	0.978
	No.1–No.3	0.654	0.365	0.839	1.000	0.998
	No.4–No.5	0.294	1.000	0.777	1.000	1.000
	No.5–No.6	0.832	0.621	0.094	0.036*	<0.001*
	No.4–No.6	0.286	0.757	1.000	0.058	<0.001*
	No.6–No.7	0.995	1.000	1.000	0.991	0.937
	No.8–No.9	0.990	1.000	0.077	0.653	<0.001*
	No.10–No.11	0.045*	0.464	0.001*	0.001*	0.075

\*Significant difference,  $p < 0.05$ .

attachments No. 1 and No. 4 were significantly different from the control (without attachment) in aligner removal from the labial side of 1 (A). In the case of removal of aligners from the labial side of 4 (B), attachments Nos. 1, 4, 5, 6, 8, 10, and 11 showed significant differences in the removal forces from that of the control. In removal of the aligner from the labial side of 6 (C), significant differences were observed in the measured removal force values between the control and attachments Nos. 1, 2, 6, 9, and 11. In removal of the aligner from the lingual side of 4 (D), significant differences were observed in the measured removal force values between control and attachments Nos. 1, 2, 3, 6, 8, 9, 10, and 11. In the case of aligner removal from the lingual side of 6 (E) of all attachments except No. 7 showed significant differences from the control. The significant differences between attachments on the first premolar indicated the importance of each site in increasing the gripping force of the aligner.

In addition, Table 9 shows the results of comparisons of the same types of attachment. There was a significant difference in the measured force values between attachments No. 2 and No. 3 for the removal of the aligner from the lingual side of 4 (D), suggesting that the aligner's gripping force decreased when the inclination angle of the edge of the MANEWVER was reduced. There was a significant difference between attachments No. 4 and No. 6 and between attachments No. 4 and No. 5 in terms of aligner removal from the lingual side of 4 (D) and the lingual side of 6 (E), suggesting that the aligner's gripping force increased with a wider diameter of the rectangular attachment. There was a significant difference between attachments No. 8 and No. 9 in the removal of the aligner from the lingual side of 6 (E), suggesting that increasing the thickness and diameter

of the ellipsoid attachment increased the gripping force of the aligner. A significant difference was observed between attachments No. 10 and No. 11 in the removal of aligners from the labial side of 1 (A) and 6 (C) and the lingual side of 4 (D), indicating that the gripping force of aligners increased with increasing thickness and diameter of the semicircular attachment.

## DISCUSSION

This study demonstrated that the placement of attachments on the teeth undergoing orthodontic treatment increases the force required to remove an aligner. The results of experiment 1 suggested that a longer aligner margin makes the aligner more difficult to remove, regardless of the removal site. Specifically, the gripping force on the teeth increased with longer aligner margins. This result was similar to that reported by Cowley *et al.*<sup>13)</sup> who suggested that the longer the margin, the more it is affected by the undercutting of the tooth surface curve. Particularly for the anterior teeth, extending the length of the margin to 2.0 mm may enhance the gripping force. It has been reported that a longer aligner edge generates a stronger force for pressure reduction in the maxillary anterior teeth and that it is effective for bite control in the anterior teeth<sup>18)</sup>.

Previous studies have evaluated aligner retention of vertically raising the bar attached to the occlusal surface of the aligner<sup>12-14)</sup>. Removing an aligner at once by applying force on a single site on the aligner could damage or deform it. Therefore, in clinical practice, patients are instructed to remove their aligners by applying force on a single site to lift the aligner, which creates room for removal, followed by gradual application

of force on a separate site to remove the aligner. The results of experiment 1 showed that the gripping force was the lowest on the lingual side of the first molar region of the aligner, indicating that the aligner removal was the easiest from this site. Irrespective of the presence of attachments, less force was required for aligner removal from the molar region compared with that from the anterior teeth region. Moreover, less force was required for aligner removal from the lingual side than from the labial side. In the mesiodistal comparison, less force was required for aligner removal from the distal side. In the labiolingual comparison, less force was required for aligner removal from the lingual side. Aligner removal from the central incisors required a large amount of force because of resistance not only from the central incisors but also because of the aligner's grip on the premolars. In contrast, when an aligner is removed from one molar region, there is no resistance from the contralateral molar region, which might have been the reason for lesser force required for aligner removal from the molar region compared with that from the central incisor region. On comparing labial and lingual side inclination angles with respect to the coronal tooth axis of the incisors, the incline is less steep on the lingual side. In the labiolingual comparison of aligner removal from the molar region, removal was more difficult from the labial side, possibly because of the morphology of the labial side of the molars. This implies that when attachments are placed on the labial side, aligner removal is conceivably affected by the gripping force of the aligner associated with those attachments. Furthermore, easy aligner removal indicates a weak grip on the teeth, which can cause the aligner to rise upward, which prevents exertion of the corrective force on the teeth.

Experiments 2 and 3 suggested that the gripping force of the aligner on the labial side of 1 (A) was increased by increasing the thickness of the rectangular attachment placed on the lateral incisor and by increasing the size of the semicircular attachment on the first premolar.

The gripping force on the labial side of 4 (B) was increased by increasing the inclination angle of the MANEWVER placed on the lateral incisor, lengthening the diameter of the rectangular attachment, and increasing the size of the ellipsoid attachment. The gripping force on the labial side of 6 (C) could be increased by increasing the inclination angle of the MANEWVER and by increasing the size of the oval attachment placed on the first premolar. The gripping force on the lingual side of 4 (D) could be enhanced by increasing the length of the rectangular attachment placed on the lateral incisor and on the first premolar, by increasing the inclination angle of the MANEWVER, and by increasing the size of the oval attachment placed on the first premolar. The gripping force on the lingual side of 6 (E) of an attachment placed on the first premolar was increased by increasing the length and diameter of the rectangular attachments placed on the lateral incisors and first premolars, and by increasing the size of the oval attachment placed on the first premolar.

In the comparison between the control (without

attachment) and attachment Nos. 1–11, the gripping force of the aligner on the buccal side of the first premolar, buccal side of the first molar, palatal side of the first premolar, and palatal side of the first molar was higher when the attachment was placed on the first premolar than when it was placed on the lateral incisor. These results can be explained by the distal placement of the attachments, which broadens the support point and mechanically stabilizes the aligner.

We also assessed aligner removability when zirconia brackets were used as attachments. Typical orthodontic brackets are ca. 0.079–0.098 inches (ca. 2.0–2.5 mm) thick, while attachments are usually 0.039 inches (ca. 1.0 mm) thick; thus, brackets are thicker than attachments<sup>19</sup>. Our results showed that zirconia brackets could be used as an attachment, with no significant difference in force during removal compared to other attachments. Furthermore, zirconia bracket can be more easily attached and removed.

We found that the undercut of the attachment is important for improving the grip of the aligner, but when the undercut is large, the aligner needs to be deflected more when it gets over the undercut. Similar to the relationship between stress-strain curves, a larger stress is required for a larger distortion. However, in our study, the deformation of the aligner after removal was not evaluated. This will be a subject of future research.

In addition, Erkodur was used as the aligner sheet material in this study. Since orthodontic forces are more efficient when sustained weak forces are applied to the teeth, aligners with gradual stress relief are ideal<sup>20,21</sup>. Erkodur is a sheet material with stable orthodontic force, which showed sustained and gradual stress relaxation in experiments that simulated the hygrothermal environment of the oral cavity<sup>22</sup>. In future studies, to evaluate the performance of aligners in the oral environment, we will apply stress to aligners in an environment that simulates the oral cavity.

An aligner that is difficult to remove is generally considered to have a high degree of gripping force, with increased corrective force on the teeth. However, we believe that further investigation is needed to determine whether a high gripping force corresponds to the exertion of corrective force by the aligner on the teeth. The corrective force at play when the same attachment form and aligner margin shape are used and the mechanism of this action must be elucidated in detail in future studies.

In this study, the mechanics of aligner removal were measured under various conditions using a custom-made measurement device. However, this study was limited in that the comfort of aligner removal was not measured in actual patients. The ease of placing and removing aligners should be evaluated in patients under conditions similar to those used in this study. In addition, since the amount of plexus in the dentition of actual patients differs, in future, mechanical measurements should be made during removal of aligners in dentition with varying amounts of plexus.

## CONCLUSIONS

This study revealed the following findings regarding aligner gripping force.

1. Aligners with longer margins were difficult to remove and had a stronger gripping force.
2. The force needed to remove an aligner was influenced by the placement site of the attachments and their morphology.
3. Aligner removal was the most difficult from the labial side of the central incisors and the easiest from the lingual side of the first molar. Removing aligners from the molar region was easier than that from the central incisor region and from the lingual side than from the labial side. Specifically, the aligner was easily lifted, and the gripping force was lower in these regions.

## REFERENCES

- 1) Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Efficacy of clear aligners in controlling orthodontic tooth movement: A systematic review. *Angle Orthod* 2015; 85: 881-889.
- 2) Boyd RL. Esthetic orthodontic treatment using the Invisalign appliance for moderate to complex malocclusions. *J Dent Educ* 2008; 72: 948-967.
- 3) Kravitz ND, Kusnoto B, Agran B, Viana G. Influence of attachments and interproximal reduction on the accuracy of canine rotation with Invisalign: A prospective clinical study. *Angle Orthod* 2008; 78: 682-687.
- 4) Sheridan JJ, Ledoux W, McMinn R. Essix appliance: minor tooth movement with divots and windows. *J Clin Orthod* 1994; 28: 659-663.
- 5) Hahn W, Dathe H, Fialka-Fricke J, Fricke-Zech S, Zapf A, Kubein-Meesenburg D, *et al.* Influence of thermoplastic appliance thickness on the magnitude of force delivered to a maxillary central incisor during tipping. *Am J Orthod Dentofacial Orthop* 2009; 136: 12 e11-e17; discussion 12-13.
- 6) Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Forces and moments generated by removable thermoplastic aligners: incisor torque, premolar derotation, and molar distalization. *Am J Orthod Dentofacial Orthop* 2014; 145: 728-735.
- 7) Hahn W, Engelke B, Jung K, Dathe H, Fialka-Fricke J, Kubein-Meesenburg D, *et al.* Initial forces and moments delivered by removable thermoplastic appliances during rotation of an upper central incisor. *Angle Orthod* 2010; 80: 239-246.
- 8) Kravitz ND, Kusnoto B, BeGole E, Obrez A, Agran B. How well dose Invisalign work? A prospective clinical study evaluating the efficacy of tooth movement with Invisalign. *Am J Orthod Dentofacial Orthop* 2009; 135: 27-35.
- 9) Djeu G, Shelton C, Maganzini A. Outcome assessment of Invisalign and traditional orthodontic treatment compared with the American Board of Orthodontics objective grading system. *Am J Orthod Dentofacial Orthop* 2005; 128: 292-298.
- 10) Boyd RL, Vlaskalic V. Three-dimensional diagnosis and orthodontic treatment of complex malocclusion with the Invisalign appliance. *Seminars Orthod* 2001; 7: 274-293.
- 11) Goto M, Yanagisawa W, Kimura H, Inou N, Maki K. A method for evaluation of effects of attachments in aligner-type orthodontic appliance: Three-dimensional finite element analysis. *Orthod Waves* 2017; 76: 207-214.
- 12) Jones ML, Mah J, O'Toole BJ. Retention of thermoformed aligners with attachments of various shapes and positions. *J Clin Orthod* 2009; 43: 113-117.
- 13) Cowley DP, Mah J, O'Toole B. The effect of gingival-margin design on the retention of thermoformed aligners. *J Clin Orthod* 2009; 46: 697-702.
- 14) Dasy H, Dasy A, Asatrian G, Rózsa N, Lee HF, Kwak JH. Effects of variable attachment shapes and aligner material on aligner retention. *Angle Orthod* 2015; 85: 934-940.
- 15) Giancotti A, Girolamo RD. Treatment of severe maxillary crowding using Invisalign and fixed appliances. *J Clin Orthod* 2009; 43: 583-589.
- 16) Lombardo L, Arreghini A, Ramina F, Huanca Ghislanzoni LT, Siciliani G. Predictability of orthodontic movement with orthodontic aligners: A retrospective study. *Prog Orthod* 2017; 18: 35.
- 17) Revision: 3. [https://www.erkodent.de/wp-content/documents/products/Erkocryl\\_PDB\\_EN.pdf](https://www.erkodent.de/wp-content/documents/products/Erkocryl_PDB_EN.pdf). Modification date: 15.04.21/created 21.10.20.
- 18) Gao L, Wichelhaus A. Force and moments delivered by the PET-G aligner to maxillary central incisor for palatal tipping and intrusion. *Angle Orthod* 2017; 87: 534-541.
- 19) Maki K, Futaki K, Tanabe S, Takahashi M, Ichikawa Y, Yamaguchi T. Applicative characteristics of a new zirconia bracket with multiple slots. *Int J Dent* 2016; 2016: 1-8.
- 20) Lombardo L, Martines E, Mazzanti V, Arreghini A, Mollica F, Siciliani G. Stress relaxation properties of four orthodontic aligner materials: a 24-hour in vitro study. *Angle Orthod* 2017; 87: 11-18.
- 21) Lombardo L, Marafioti M, Stefanoni F, Mollica F, Siciliani G. Load deflection characteristics and force level of nickel titanium initial archwires. *Angle Orthod* 2012; 82: 507-521.
- 22) Dongyu F, Ning Z, Hui C, Yuxing B. Dynamic stress relaxation of orthodontic thermoplastic materials in a simulated oral environment. *Dent Mater J* 2013; 32: 946-951.