

Comparative assessment of forces generated during simulated alignment with self-ligating and conventional brackets

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SUMMARY The objectives of this study were to comparatively assess the magnitude and direction of forces and moments generated from different bracket systems, during the initial levelling and alignment stage of orthodontic treatment. Three types of brackets were used: Orthos2 (Ormco), Damon2 (Ormco), and In-Ovation R (GAC). The brackets were bonded on resin replicas models of a patient's crowded mandibular arch, and a 0.014 inch Damon archform CuNiTi (Ormco) wire was inserted. The model was mounted on the Orthodontic Measurement and Simulation System (OMSS) and six static measurements were taken at the initial crowded state per bracket for the lateral incisor, canine, and first premolar. A total of 10 repetitions were performed for each measurement, with new brackets and archwires used for each trial. The forces and moments generated were registered directly on the OMSS software and were statistically analyzed using a one-way analysis of variance separately for each dental arch location and force component. Group differences were further analyzed with Tukey's *post hoc* comparisons test at the 0.05 significance level.

The lingually inclined, crowded lateral incisor presented an extrusive and buccal movement and showed the lowest force in the vertical direction, whereas the self-ligating group of brackets generated the highest force in the buccolingual direction. The moments applied by the three bracket systems followed the general trend shown for forces; in the vertical axis, the self-ligating brackets exerted lower forces than their conventional counterpart. This was modified in the buccolingual direction where, in most instances, the self-ligating appliances applied higher moments compared with the conventional bracket. In most cases, the magnitude of forces and moments ranged between 30–70 cN and 2–6 N mm, respectively. However, maximum forces and moments developed at the lateral incisor were almost four times higher than the average.

Introduction

The incorporation of self-ligating brackets into routine clinical practise aimed at replacing existing conventional ligation methods with elastomeric and stainless steel ligatures in order to improve clinical efficacy (Hanson, 1980; Damon, 1998; Voudouris and Kuflinec, 2006). Consistent archwire engagement throughout orthodontic treatment and elimination of the need for frequent visits for the replacement of ligatures were the main advantages listed for the new ligation mode (Shivapuja and Berger, 1994; Harradine, 2003). Additionally, it has been proposed that due to the bracket–wire engagement, generation of light forces and reduced friction are attained with a desirable outcome on the rate of orthodontic tooth movement. For a given cross-section and modulus of archwire, the magnitude of force developed during engagement may vary depending on the interbracket span, ligation mode, and number of teeth ligated in the proximal and distal segments of the arch. This effect arises from the increased stiffness of the wire–bracket complex associated with the presence of many dental units incorporated into the mechanotherapy (Drenker, 1988). Additional factors, which modulate force magnitude may relate to the degree of crowding, which is associated with interbracket distance, the relaxation of ligatures and clip

modulus of elasticity, and relaxation of self-ligating bracket-engaging mechanism (Pandis *et al.*, 2007), which may alter or modify the load transmitted to the teeth (Iwasaki *et al.*, 2003). Despite the emphasis placed on the necessity of applying light forces, a scarcity of evidence exists on the forces and moments generated during activation of an archwire in self-ligating brackets in a crowded arch scenario (Berger, 1990, 1994). Therefore, most manufacturers' claims are based on assumptions, which have never been directly validated.

The purpose of this research was to comparatively assess the magnitude of forces and moments generated from different bracket systems, during the initial levelling and alignment stage of orthodontic treatment.

Materials and methods

Resin replicas (Palavit G, Heraeus Kulzer GmbH, Hanau, Germany) were constructed from the original mandibular plaster model of a patient, representing a routine mandibular crowded case (Figure 1).

Three bracket types were included in the study: conventional Orthos2 (Ormco, Glendora, California, USA), passive self-ligating Damon2 (Ormco), and active self-ligating In-Ovation

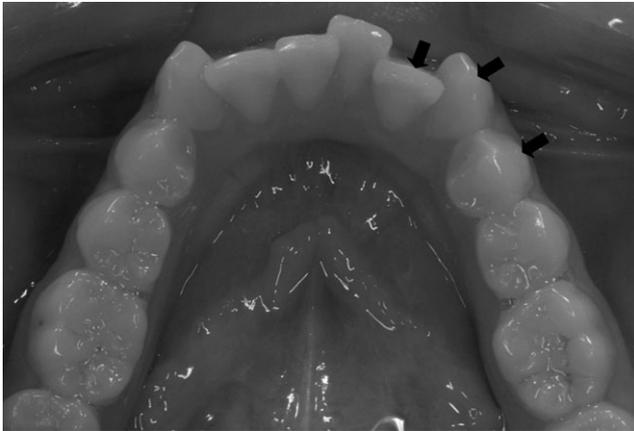


Figure 1 Occlusal view of the mandibular dental arch used as a model for the assessment of forces during alignment with engagement of a 0.014 NiTi archwire into the slots of the three bracket types included in the study. Force registration was made at the right lateral incisor, canine, and first premolar.

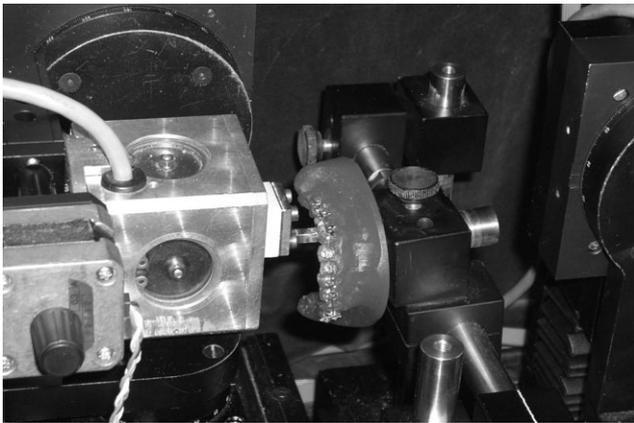


Figure 2 The resin replica of the model mandibular arch mounted on the Orthodontic Measurement and Simulation System.

R bracket (GAC, Bohemia, New York, USA) all with a 0.022 inch slot and the same prescription. The brackets were bonded to the resin replicas from second premolar to second premolar.

Orthodontic levelling and aligning at different dental arch locations and with variable degrees of misalignment were simulated on the Orthodontic Measurement and Simulation System (OMSS). The three locations where measurements were performed were the lateral incisor, canine, and first premolar of the right quadrant. A static measurement of the forces produced in the three planes of space was performed at the time the wire was engaged into the misaligned dental arch.

A 0.014 inch CuNiTi, Damon archform wire (Ormco), was inserted into the brackets of the resin model and the latter was mounted sequentially on the OMSS table while the corresponding bracket of the location-tooth of interest, which was removed from the model, was mounted on a special base fitted on the OMSS sensor (Figure 2). The

major components of the OMSS are two force–moment sensors capable of simultaneously measuring forces and moments in all three planes of space (Drescher *et al.*, 1991; Bourauel *et al.*, 1992). The two sensors are mounted on motor-driven positioning tables with full three-dimensional mobility, whereas all mechanical components are built in a temperature-controlled chamber, interfaced with a computer. This system is capable of performing various types of measurement, and the resultant force–deflection curves are recorded, thus facilitating a means to study the loads arising from simulated orthodontic tooth movement.

Once the constructed model was mounted on the OMSS table and the corresponding bracket on the OMSS sensor, the model and bracket were positioned in such a way that they simulated the archform of the original dental arch. Six wire–bracket sets were tested for each appliance, and a total of 10 repetitions were performed for each measurement, with new brackets and archwires used for each trial. The forces and moments generated from each trial were registered directly on the OMSS software. The orientation of the model on the OMSS resulted in the following force and moment components/directions:

Fx: In–out (buccolingual) movement	±: buccal movement of the tooth
Fy: Vertical (intrusion–extrusion) movement	+: intrusion of the tooth
Fz: Mesial–distal component movement	+: distal movement of the tooth
Mx: moment around the buccolingual axis	+: buccal tipping of the tooth
My: moment around the vertical axis	+: mesial rotation of the tooth
Mz: moment around the mesial–distal axis	+: buccal crown torque

The Fz component was not included in the analysis because of its minute range and limited significance, resulting from its direction along the engaged archwire, making the force transmission along the long axis of the wire unlikely. Similarly, data for the Mz moment were excluded because it was considered that a round wire would produce negligible, if any, torquing moment around the mesiodistal axis.

The force and moment values were statistically analyzed, using a one-way analysis of variance procedure, separately for each dental arch location–tooth, and force and moment component registered in the three planes of space. Group differences were further analyzed with Tukey's *post hoc* comparisons test at the 0.05 significance level. All statistical analyses were performed using the Minitab version 14.1 Statistical Package (Minitab Inc., State College, Pennsylvania, USA).

Results

Table 1 shows the mean values obtained from the static measurements after initial wire engagement. The wire clearly induced an extrusive force for all bracket types, which was of significantly lower magnitude for the Damon2 bracket compared with both the conventional and In-Ovation R. For buccolingual movement, however, the rankings were reversed, with the Damon2 bracket showing significantly higher forces relative to the conventional appliance but not the In-Ovation R. The forces generated by the In-Ovation R did not differ significantly from the conventional or Orthos2 appliance.

The corresponding force magnitudes registered at the canine are also shown in Table 1. In this case, in the vertical axis, the movement was similar to the lateral incisor implying an extrusive component, which was significantly greater in the Damon2 group relative to the other brackets. On the contrary, buccolingual displacement of the canine seems to be in the opposite direction of that found for the lateral incisor, with all brackets generating similar force magnitudes.

The loads developed at the first premolar during alignment are shown in Table 1. Both self-ligating brackets demonstrated lower forces relative to their conventional counterpart in the vertical plane (intrusion-extrusion), whereas the greatest forces were registered for the Damon2 in the horizontal (buccolingual) direction.

Table 2 depicts the corresponding maximum moment values registered during wire engagement at the three arch locations, that is lateral incisor, canine, and premolar.

The moments developed at the lateral incisor are shown in Table 2. In the vertical axis, the In-Ovation R brackets showed the lowest moment followed by the conventional appliance, and the Damon2 exerted the highest moment. In

the buccolingual direction, the rankings of moments were modified, with the conventional bracket presenting the lowest moment and the self-ligating appliances showing an almost 100 per cent increase. No difference was noted between the Damon2 and In-Ovation R brackets for this movement.

The highest moments at the canine were obtained with the conventional appliance followed by the In-Ovation R and the Damon2 (Table 2). Compared with the data for the lateral incisor, it can be seen that the ranking was reversed in the buccolingual direction, where the conventional appliance showed a force more than two times lower than the Damon2 bracket and 80 per cent reduced force compared with the In-Ovation R.

In the vertical direction, the Damon2 showed the lowest moment followed by In-Ovation R and the conventional bracket. In the buccolingual direction, the Damon2 and conventional showed the same levels of moments, whereas the In-Ovation R applied lower moments (Table 2).

Discussion

The model utilized in this study simulated the movement of teeth routinely encountered in a crowded mandibular arch. While conventional and active self-ligating brackets do not employ similar mechanotherapeutic guidelines, the 0.014 inch NiTi archwire in a 0.022 inch slot represents a feasible alternative for a standard wire sequence in a crowded case. Despite the fact that the results of this study derive from a model of the dental arch, the results are representative of the variables examined in a routine case. Inclusion of various degrees of crowding and different archform configurations (constricted, asymmetric, etc.) would incorporate additional parameters in the analysis while offering no further value.

Table 1 Means and standard deviations (SD) of maximum force values in Newtons (N) recorded at the teeth during alignment of the mandibular arch with the three bracket types included in the study.

Bracket	Maximum forces					
	Lateral incisor		Canine		First premolar	
	Fy intrusion-extrusion	Fx buccal-lingual	Fy intrusion-extrusion	Fx buccal-lingual	Fy intrusion-extrusion	Fx buccal-lingual
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Damon2	-0.15 (0.10) ^a	2.34 (0.14) ^a	-0.56 (0.11) ^a	-1.33 (0.16) ^a	-1.67 (0.04) ^a	0.41 (0.17) ^a
In-Ovation R	-0.62 (0.14) ^b	2.25 (0.30) ^a	-0.25 (0.05) ^b	-0.58 (0.05) ^b	-1.10 (0.20) ^b	-0.09 (0.02) ^b
Orthos2	-0.81 (0.13) ^c	1.43 (0.09) ^b	-0.49 (0.06) ^a	-0.86 (0.03) ^c	-1.44 (0.06) ^c	0.61 (0.19) ^c

Means with the same letters are not significantly different at the 0.05 level.

Negative sign denotes extrusion in the Fy and lingual movement in the Fx direction.

Comparisons involved the absolute values of means and apply to column values only (among brackets for the same force component).

Table 2 Means and standard deviations (SD) of maximum moment values recorded at the three teeth during alignment of the mandibular arch with the three bracket types included in the study.

Bracket	Maximum moments					
	Lateral incisor		Canine		First premolar	
	My (vertical axis moment; N mm)	Mx (buccal–lingual moment; N mm)	My (vertical axis moment; N mm)	Mx (buccal–lingual moment; N mm)	My (vertical axis moment; N mm)	Mx (buccal–lingual moment; N mm)
	Mean	Mean (SD)	Mean	Mean (SD)	Mean	Mean (SD)
Damon2	3.68 (0.90) ^a	–19.89 (1.06) ^a	–1.34 (0.79) ^a	11.25 (2.75) ^a	–1.23 (0.38) ^a	–6.16 (1.27) ^a
In-Ovation R	0.22 (0.19) ^b	–18.80 (2.74) ^a	2.66 (0.49) ^b	7.48 (2.42) ^b	–1.68 (0.42) ^b	–5.10 (0.80) ^b
Orthos2	1.84 (0.82) ^c	–10.59 (1.66) ^b	6.74 (0.72) ^c	4.96 (1.01) ^c	3.73 (1.06) ^c	–6.44 (1.88) ^a

Means with the same letters are not significantly different at the 0.05 level.

Negative sign denotes lingual tipping in the My and distal rotation in the Mx direction.

Comparisons involved the absolute values of means and apply to column values only (among brackets for the same moment component).

Additional research could reveal the relationship of force or moment generation with regard to the irregularity index.

Because of the lack of a periodontal ligament, the results of this study represent the values of forces and moments applied by the engaged archwire in the brackets studied; thus, the actual force and moment experienced by the tooth may vary since the mechanical properties of the periodontal ligament affect the transmission of loads. However, a reliable medium, which could simulate the response of this ligament to forces has not yet been developed and therefore, the use of elastic material or other substitutes for the purpose of extrapolating the biological impact of loads is an oversimplification of the phenomena occurring *in vivo*.

Potential differences in the values reported in this study and previous investigations examining self-ligating brackets should be assigned, among other minor influences, primarily to the different types of closing mechanisms among self-ligating appliances, different bracket widths, and varying bracket slot/archwire play. Moreover, the configuration of the present experimental set-up involved the investigation of forces in a mandibular arch of 10 teeth in contrast to the engagement of a single tooth (Schudy and Schudy, 1989; Sander *et al.*, 2006) in similar approaches, a fact, which may greatly differentiate the forces developed. It must be noted, however, that the values reported apply only to the specific experimental configuration employed and are valid only for the tooth/archform/interbracket distance tested. Therefore, even though the case selected represents a frequently encountered mandibular arch, no generalization of the absolute values obtained should be made to every archform/crowding variants and malocclusions.

The reduction in force levels in certain directions for self-ligating brackets may be due to the increased play of wires in the slot and the lack of obstacles arising from the contact of an elastomeric ligature outside the wings. Variations in

the design of the closing mechanism of the two self-ligating bracket included in the study may affect the force generated by the displaced bracket, as force direction on the lingual movement of the bracket coincides with the compliant section of the bracket slot. The stiffness and rigidity of the Damon2 buccal slot wall may be a limiting factor, which does not allow movement of the wire as the bracket is forced lingually and the wire comes in contact with the outer slot wall. In contrast, the elastically deformed clip of the In-Ovation R bracket provides flexibility as the wire is pressed against the buccal clip. Whereas conventional brackets do not possess this fourth wall, the use of a new elastomeric ligature may also restrict archwire movement. Additionally, a source of variability is the ageing alterations of the clip of active self-ligating brackets occurring during the course of orthodontic treatment, and which may modify the forces generated during wire engagement (Pandis *et al.*, 2007).

It is interesting to note that forces were generally in the order of 30–80 cN with the exception of buccal movement of the lateral incisor, which reached 200–250 cN and some other buccolingual correction of the premolar. Moreover, the results of this study imply that interbracket distance alone is not a reliable predicting factor of force magnitude during archwire engagement. This is clearly illustrated in the results for the bracket with the least width (Damon2), which showed force levels, which were lower for certain teeth and direction of movement combinations and higher in others, implying that the effect of ligating mode prevails over interbracket distance.

The moment data obtained for the three brackets on the selected teeth verify the effect of direction of movement on modification of loads and moments on teeth. Whereas there was a trend for the self-ligating brackets to show decreased moments in the vertical axis for all three teeth, the rankings

of moments exerted by each appliance were modified, and in some cases almost reversed when the direction was changed to buccolingual. This variation should be assigned to the stiffness of the closing component of the slot which, when not rigid, relaxes thereby lowering the force applied on the tooth. While some of the statistical differences between values may not have clinical significance, for some movements these differences were exceedingly high. For example, the Damon2 bracket generated a moment for the crowded lateral incisor of the order of 20 N mm, while the conventional appliance showed about half of that value for the same tooth. On the contrary, in cases where the conventional bracket showed higher moments than the self-ligating appliances, as in the case of the canine in the vertical axis, the absolute values for moments were much lower than the corresponding maxima for self-ligating brackets, that is 6.5 versus 19.5 N mm.

The relevant literature of studies examining the magnitude of forces developed during engagement of archwires into the slot of conventional and self-ligating brackets is limited. Even fewer studies present a configuration, which involves registration of forces on multiple regions in the dental arch on tooth crowns and not archwire loads. Such an investigation was carried out by Kasuya *et al.* (2007), who measured the force levels corresponding to the unloading portion of the curve of archwires during first-order deflection of various ligation modes in lower incisor brackets mounted on metal beams, where a 0.016 inch NiTi wire and a maximum deflection of 1500 μm were used. Those authors found that ligation with elastomerics generated higher loads compared with passive self-ligation. However, the materials and the methodology included in their research were different from that used in the present investigation and in essence possess no clinical relevance. On the contrary, Hemingway *et al.* (2001), using an experimental configuration, which resembled that utilized in the present research, incorporating a full bonded arch and 0.014 inch NiTi archwire, found greater variability among the different brackets with regard to the unloading forces. Moreover, in specific areas of the arch, the unloading forces recorded were higher for the passive self-ligating brackets, which was also found in the present study.

The results of this investigation suggest that for a given archwire, there are complex bracket–archform and tooth relationships, which modulate the magnitude and direction of forces, and that the increased wire–bracket free play cannot reliably predict the loads exerted by self-ligating brackets.

Conclusions

Variations in force level among the three brackets tested in this study followed a complex pattern and seem to be influenced by multiple factors including ligation mode, bracket width, archform, and tooth position, each contributing with variable weightings depending on the specific characteristics of the dental arch and the wire.

The lingually inclined, crowded lateral incisor presented an extrusive and buccal movement, with the Damon2 bracket showing the lowest force in the vertical plane (intrusion–extrusion) and the self-ligating group of brackets generating the highest force in the buccolingual direction.

Loads exerted by brackets to the canine tended to extrude the tooth and position it lingually, with the Damon2 generating the highest vertical forces; no difference was found among the three brackets with respect to buccolingual movements.

Alignment-induced forces applied on the premolar in the vertical plane were higher for the conventional bracket, whereas buccolingual movement with the Damon2 was associated with increased loads relative to other brackets.

The moments applied by the three bracket systems followed the general trend shown for forces; in the vertical axis, the self-ligating brackets exerted lower forces than their conventional counterpart. This was modified in the buccolingual direction where, in most cases, the self-ligating appliances applied higher moments compared with the conventional bracket. However, in cases where the conventional bracket showed higher moments, the absolute values were in the order of 6 N mm, which was much lower than the corresponding maxima for self-ligating brackets, which reached 19 N mm.

In most cases, the magnitude of forces and moments ranged within 30–70 cN and 2–6 N mm, respectively. However, maximum forces and moments developed at the lateral incisor were almost four times higher than the average.

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