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Conventionally ligated versus self-ligating metal brackets—a comparative study

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SUMMARY The purpose of this study was to compare the frictional properties of four self-ligating metal brackets, Speed, Damon 2, In-Ovation, and Time, with those of three conventionally ligated metal brackets, Time, Victory Twin, and Discovery. The self-ligating Time bracket can also be used as a conventionally ligated bracket. Friction was tested 20 times for each bracket/wire combination using a Zwick testing machine with stainless steel wires in three different wire dimensions (0.017 × 0.025, 0.018 × 0.025, and 0.019 × 0.025 inches). All brackets had a 0.022 inch slot and the prescription of an upper first premolar. The data were statistically analysed with unsigned comparisons of all bracket/wire combinations using the Mann–Whitney *U*-test and the Games–Howell *post hoc* test.

The results showed almost all brackets to have the lowest frictional force with a wire dimension of 0.018 × 0.025 inch. Friction of the self-ligating brackets using wire with a dimension of 0.018 × 0.025 inches was 45–48 per cent lower than with 0.017 × 0.025 and 0.019 × 0.025 inch wires. Friction of the conventionally ligated brackets showed a 14 per cent or less reduced friction with 0.018 × 0.025 inch wire compared with 0.017 × 0.025 and 0.019 × 0.025 inch wires. The self-ligating metal brackets showed lower frictional forces with a 0.018 × 0.025 inch wire than conventionally ligated brackets, whereas conventionally ligated brackets showed lower friction with 0.017 × 0.025 and 0.019 × 0.025 inch wire.

Friction values vary with different bracket/archwire combinations and, therefore, the choice of a bracket system for treatment should consider the correct wire dimension to produce the lowest possible frictional forces.

Introduction

Friction between the bracket and archwire has gained importance since the increased use of sliding mechanics that followed the development of the pre-adjusted edgewise systems. Since friction reduces the effectiveness of tooth movement along the wire, significant efforts were made to lower friction in orthodontics.

Frictional resistance between archwire and brackets is determined by many factors and varies with wire to bracket angulation (Andreasen and Quevedo, 1970; Dickson *et al.*, 1994), archwire size and material (Angolkar *et al.*, 1990; Ireland *et al.*, 1991), mode of ligation (Bednar *et al.*, 1991; Sims *et al.*, 1993; Taylor and Ison, 1996), biological resistance (Drescher *et al.*, 1989), saliva (Kusy *et al.*, 1991; Downing *et al.*, 1995), and bracket width (Frank and Nikolai, 1980; Drescher *et al.*, 1989). Drescher *et al.* (1989) considered bracket width to play an inferior role in frictional forces. Since the mid-1970s, the search for a bracket system with a low frictional resistance resulted in a renewed interest in the development of self-ligating brackets. Two different types of self-ligating brackets were produced: active brackets, that feature a spring clip actively pressing against the archwire, e.g. the Speed bracket, and passive brackets, whose self-ligating clip does not press against the wire, e.g. the Damon bracket.

According to the manufacturers, these self-ligating brackets should not only be easier to handle in the ligation process but also show lower frictional forces than conventionally ligated brackets. Thus, the following question arises: are the frictional properties of self-ligating brackets better than those of conventionally ligated brackets with all wire dimensions, or do their frictional properties vary with different bracket/archwire combinations.

Therefore, the purpose of this study was to compare the frictional properties of four self-ligating and three conventionally ligated metal brackets by determining the force required to pass three standard clinical archwires through these brackets *in vitro*.

Materials and methods

Bracket systems and wires

Four types of self-ligating metal brackets, Speed (Strite Industries Ltd, Cambridge, Ontario, Canada), Damon 2 (Ormco, Orange, California, USA), In-Ovation (GAC Int., Bohemia, New York, USA), and Time (Adenta, Gilching, Germany), as well as the three different types of conventionally ligated metal brackets Time (Adenta), Victory Twin (3M Unitek, Monrovia, California, USA), and

Discovery (Dentaurum J. P. Winkelstroeter KG, Ispringen, Germany) were tested. While the self-ligating brackets, Speed, In-Ovation, and Time, are interactive brackets, the Damon 2 is a non-interactive so-called passive self-ligating bracket. The Time bracket can be used either as self-ligating or conventionally ligated bracket. The bracket specifications are summarized in Table 1.

Ten brackets of each type were ligated to rectangular stainless steel (SS) archwires (Dentaurum) that had three different dimensions 0.017 × 0.025, 0.018 × 0.025, and 0.019 × 0.025 inches and came from plain strands of wire. The conventional brackets were ligated with elastic modules (Dentalastics, Dentaurum) in order to prevent individual differences in forces resulting from ligature wires. All brackets, except Damon 2, used in this study had a 0.022 × 0.028 inch slot and the prescription of an upper first premolar of the Roth system (tip = 0 degree; torque = –7 degrees). The Damon 2 bracket for an upper first premolar had a 0.022 × 0.027 inch slot, a torque of –7 degrees and tip of +2 degrees.

The tolerance of slot and wire sizes is usually the responsibility of the manufacturers' quality control management. Random testing of the slot and wire sizes indicated by the manufacturers failed to reveal serious deviations.

Experimental set-up

The brackets were bonded centrally onto a round metal base that had been sandblasted to improve retention. To ensure correct positioning of the wire–bracket couples on the metal base, the following technique was used: two identical standard edgewise 0.022 inch brackets (tip = 0 degree; torque = 0 degree) were bonded onto a flat aluminium plate in a straight line. This position was secured by ligating these brackets to a straight piece of a 0.022 × 0.025 inch SS wire before bonding. The plate was mounted centrally to the model table of the milling machine 'Degussa F2' (Degudent, Hanau, Germany). Each round metal base was fixed in the milling machine and adjusted in such a way that its centre corresponded with the centre of the tested bracket. Bracket bases were supplied with the primer Exite (Ivoclar Vivadent, Ellwangen, Germany) and the light curing composite Tetric Flow (Ivoclar Vivadent). The metal base-holding part of the milling machine was then lowered vertically towards the bracket base ensuring parallelism between the metal base surface and bracket–wire couple. Finally, the composite was cured for 60 seconds with a halogen light, Ortholux XT (3M Unitek).

Friction was tested with a universal test machine (Model 1446, Zwick, Ulm, Germany). This experimental set-up consisted of a metal framework (Figure 1), which allowed rotation of the metal base bonded to the bracket/wire unit in order to simulate the continuous tipping–uprighting sliding movement of bonded teeth. Two guide rollers were placed above and below the metal base to guide the movement of the wire. A 12 mm piece of metal was attached to this metal base, from which a 250 g weight was suspended to increase wire binding at the edges of the bracket during sliding and therefore simulate the clinical situation of an angulation effect.

Each rectangular SS wire was pulled through twice with a constant velocity of 12.7 mm/minute (Bednar *et al.*, 1991). Other studies using different speeds ranging from 0.5 to 50 mm/minute showed no significant differences in friction measurements (Ireland *et al.*, 1991; Taylor and Ison, 1996). Each bracket was pulled 10 mm along the wire and the maximum frictional forces were measured. Altogether, 60 tests per bracket type were carried out.

Statistical analysis

Statistical analysis was undertaken with the Statistical Package for Social Sciences, Version 12.0 for Windows (SPSS Inc., Chicago, Illinois, USA), and the results were considered as significant at $P \leq 0.05$. With the chosen sample size of $n = 20$ per unit of analysis (bracket/archwire combination), a minimum statistical power of 0.80 was estimated for each two-sided comparison. The data were presented graphically by box and whisker plots using SigmaPlot 10.0 (Systat Software GmbH, Erkrath, Germany). Normal distribution of the data was tested using the Kolmogorov–Smirnov test, and the homogeneity of variance

Table 1 Bracket characteristics and prescription.

	Bracket system					
	Speed	Damon 2	In-Ovation	Time	Victory Twin	Discovery
Manufacturer	Strite Industries Ltd	Ormco	GAC Int.	Adenta	3M Unitek	Dentaurum J. P. Winkelstroeter KG
Type	Self-ligating	Self-ligating	Self-ligating	Self-ligating and conventional	Conventional	Conventional
Material	Metal bracket	Metal bracket	Metal bracket	Metal bracket	Metal bracket	Metal bracket
Bracket width (mm)	1.7	2.6	3.2	2.5	3.0	3.3
Slot size (inches)	0.022	0.022	0.022	0.022	0.022	0.022

with Levene's test. Since the data showed normal distribution but no homogeneity of variance, frictional forces were evaluated with unsigned comparisons of all bracket-wire combinations using Mann–Whitney's *U*-test and analysed *post hoc* using the procedure of Games–Howell for control of the multiple comparisons.

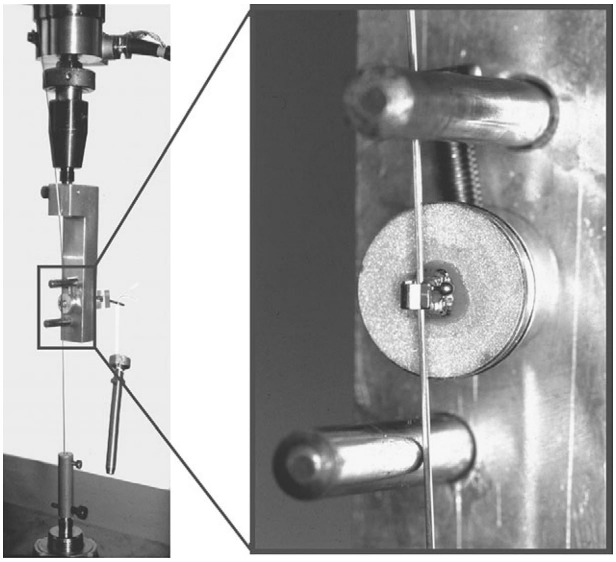

Figure 1 Experimental set-up fixed in the Zwick testing apparatus. The metal framework allowed rotation of the metal base bonded to the bracket/wire unit. An attached 250 g weight simulated angulation by increasing wire binding at the edges of the bracket during sliding. The magnified detail shows the wire fixed in the bracket with two rollers guiding the wire movement.

Results

Table 2 summarizes friction data and mean frictional forces of the four self-ligating and three conventionally ligated metal brackets for the three different wire dimensions. Pairwise comparisons between all wire dimensions and bracket types were calculated using the Mann–Whitney *U*-test (Table 3). The results showed that the frictional properties of the different brackets depended mainly on the different wire dimensions. As visualized by the boxplots (Figure 2), the self-ligating brackets showed lower frictional values than the conventionally ligated brackets only with 0.018 × 0.025 inch SS wire. With the wire dimensions 0.017 × 0.025 and 0.019 × 0.025 inch, the conventionally ligated brackets demonstrated lower frictional forces than the self-ligating brackets.

Almost all brackets showed the lowest frictional values with 0.018 × 0.025 inch wire. The only exception was the conventionally ligated Time bracket. The lowest friction for this bracket was found in combination with 0.019 × 0.025 inch wire.

A comparison of the pooled group of self-ligating brackets with the pooled group of conventionally ligated brackets at the three different wire dimensions revealed that friction was higher in the self-ligating group with 0.017 × 0.025 and 0.019 × 0.025 inch SS wires than in the conventionally ligated group (Table 4). Self-ligating brackets had the lowest frictional values with 0.018 × 0.025 inch wire, with friction being lower than with the conventionally ligated brackets.

Self-ligating brackets in combination with 0.018 × 0.025 inch wire showed a 45–48 per cent reduction in friction (calculated from the mean; Table 4) in comparison with

Table 2 Statistical summary of friction data for all bracket/archwire combinations.

Bracket system	Archwire type	Archwire size (inches)	*n*	Mean (N)	SD (N)	Median (N)	Interquartile range (Q3–Q1, N)	Minimum (N)	Maximum (N)
Speed	Stainless steel	0.017 × 0.025	20	12.7	2.9	12.1	3.7	8.1	21.5
		0.018 × 0.025	20	6.6	1.9	6.3	2.1	2.5	10.4
		0.019 × 0.025	20	12.0	2.2	11.9	3.3	8.5	16.2
Damon 2	Stainless steel	0.017 × 0.025	20	11.9	2.5	11.5	3.6	7.3	16.4
		0.018 × 0.025	20	5.9	2.5	5.7	4.5	2.1	10.7
		0.019 × 0.025	20	8.9	2.6	9.1	5.0	5.3	12.7
In-Ovation	Stainless steel	0.017 × 0.025	20	11.0	2.3	10.8	3.0	7.3	15.9
		0.018 × 0.025	20	7.3	2.4	7.2	3.1	4.1	13.8
		0.019 × 0.025	20	12.5	4.2	13.2	5.9	5.9	23.2
Time (self-ligating)	Stainless steel	0.017 × 0.025	20	10.2	2.5	9.8	3.5	6.5	17.0
		0.018 × 0.025	20	4.9	1.7	5.1	2.7	2.1	7.9
		0.019 × 0.025	20	14.4	3.0	13.6	4.0	10.6	20.4
Time (conventionally ligated)	Stainless steel	0.017 × 0.025	20	9.2	4.7	7.6	6.7	3.6	19.8
		0.018 × 0.025	20	9.2	4.3	7.1	7.0	5.1	20.0
		0.019 × 0.025	20	6.1	2.4	5.7	3.0	2.1	11.4
Victory Twin	Stainless steel	0.017 × 0.025	20	9.6	1.9	9.5	1.9	6.8	15.2
		0.018 × 0.025	20	7.6	2.6	7.1	3.3	2.5	12.9
		0.019 × 0.025	20	8.6	2.4	8.6	3.6	5.2	13.5
Discovery	Stainless steel	0.017 × 0.025	20	9.8	2.0	9.5	2.5	7.1	15.1
		0.018 × 0.025	20	8.0	2.8	6.8	4.2	5.0	14.7
		0.019 × 0.025	20	9.4	2.5	8.9	4.0	5.0	14.1

SD, standard deviation.

Table 3 Statistical summary of friction data of the tested brackets Speed, Time (s), Damon 2, In-Ovation, Victory Twin, Discovery, and Time (c) with stainless steel wire dimensions 0.017 × 0.025, 0.019 × 0.025, and 0.019 × 0.025 inch.

	Wire dimension (inches)	Speed	Time (s)	Damon 2	In-Ovation	Victory Twin	Discovery	Time (c)
Speed	0.017							
	0.018							
	0.019							
Time self-ligating (s)	0.017	0.0025*						
	0.018	0.0036*						
	0.019	0.0196*						
Damon 2	0.017	0.3865	0.0359*					
	0.018	0.1351	0.2247					
	0.019	0.0026*	0.0000*					
In-Ovation	0.017	0.0514	0.2132	0.1635				
	0.018	0.6097	0.0410*	0.0842				
	0.019	0.5741	0.3233	0.0018*				
Victory Twin	0.017	0.0001*	0.4169	0.0015*	0.0238*			
	0.018	0.4260	0.0010*	0.0467*	0.6231			
	0.019	0.0002*	0.0000*	0.5336	0.0005*			
Discovery	0.017	0.0005*	0.5882	0.0035*	0.0763	0.7351		
	0.018	0.1876	0.0002*	0.0140*	0.3382	0.2035		
	0.019	0.0047*	0.0000*	0.6358	0.0077*	0.5785		
Time conventionally	0.017	0.0026*	0.0933	0.0077*	0.0256*	0.2036	0.1366	
ligated (c)	0.018	0.3542	0.0003*	0.0152*	0.3578	0.5513	0.8390	
	0.019	0.0000*	0.0000*	0.0013*	0.0000*	0.0020*	0.0001*	

The significance of testing in pairs is shown (unsigned comparisons with Mann–Whitney's *U*-test).
$*P \leq 0.05$ ($n = 20$ for each configuration). SS, stainless steel.

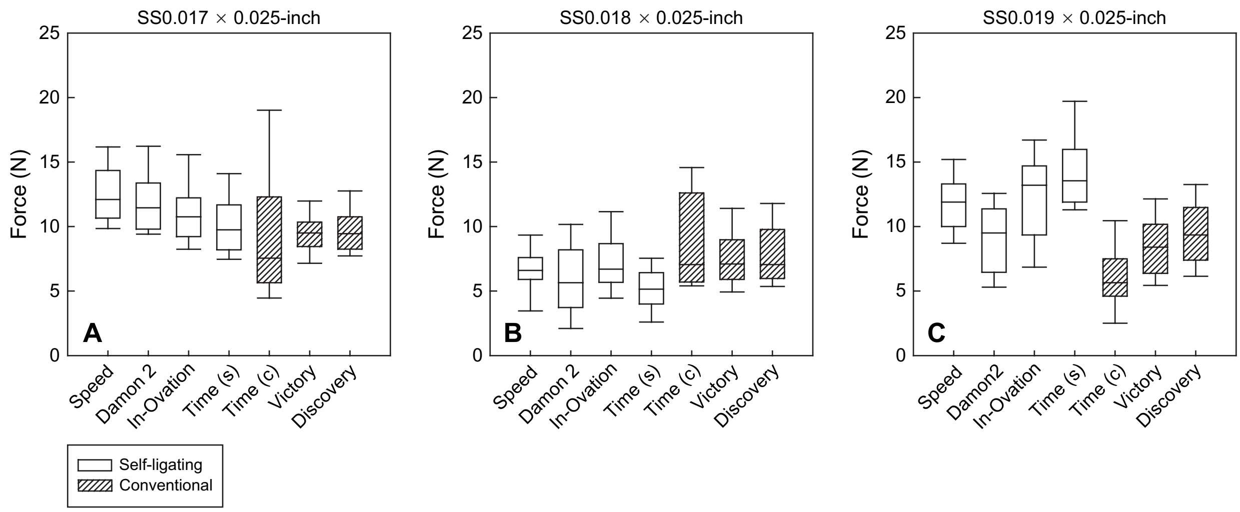

Figure 2 Boxplots showing the maximum frictional forces of the bracket systems Speed, Damon 2, In-Ovation, Time (s) self-ligating, Time (c) conventionally ligated, Victory Twin, and Discovery depending on the wire dimensions used: (A) stainless steel (SS) 0.017 × 0.025 inch, (B) SS 0.018 × 0.025 inch, and (C) SS 0.019 × 0.025 inch. The height of the box corresponds to the interquartile range (3rd to 1st quartile) and the line in the box to the median.

wire dimensions of 0.017 × 0.025 and 0.019 × 0.025 inches. With the conventionally ligated brackets with 0.017 × 0.025 and 0.019 × 0.025 inch wires, differences in frictional forces amounted to only about 14 per cent or less in comparison with the 0.018 × 0.025 inch wire (calculated from the mean; Table 4).

In the group with 0.018 × 0.025 inch wire, the self-ligating brackets showed a median frictional force of 6.1 N, a maximum of 13.8 N, and a minimum of 2.1 N. For the conventionally ligated brackets with the same wire dimension, the frictional forces were 7.1, 20.0, and 2.5 N, respectively. With 0.019 × 0.025 inch wire, the median of the self-ligating brackets was 11.9 N while that of the conventionally ligated brackets amounted only to 7.9 N. With 0.017 × 0.025 inch wire, the median of the self-ligating brackets was 11.1 N and that of the conventionally ligated brackets 9.4 N.

The Time bracket can be used as a self-ligating bracket with a clip, if for any reasons the clip is lost, as a conventionally ligated bracket and therefore allows direct comparison of friction. Figure 3 shows the frictional forces of the conventionally ligated compared with the self-ligating Time bracket at the different wire dimensions. The self-ligating Time bracket showed the largest frictional differences of all self-ligating brackets with the three different wire dimensions. The medians were 9.8 N for 0.017 × 0.025, 5.1 N for 0.018 × 0.025, and 13.6 N for 0.019 × 0.025 inch wire. In contrast, using the Time bracket as a conventionally ligated bracket with an elastic ligature yielded a markedly smaller range of mean frictional forces at the different wire dimensions varying between 5.7 N with a 0.019 × 0.025 inch, 7.1 N with 0.018 × 0.025 inch, and 7.6 N with 0.017 × 0.025 inch. However, the standard deviations in general were higher than those of the self-ligating Time bracket. The difference in frictional force between the self-ligating and conventionally ligated Time bracket was significant with wires with a dimension of 0.018 × 0.025 (P = 0.0003) and 0.019 × 0.025 inches (P = 0.0000).

Discussion

This laboratory study was designed to compare the friction produced by self-ligating and conventionally ligated metal brackets at different wire dimensions.

Certain wire grades and sizes are recommended by the manufacturers for various reasons.

Data for self-ligating and conventional brackets were pooled. As most self-ligating brackets were somewhat narrower compared with the conventional brackets, precautions were taken to minimize confounding bracket type and width. Therefore, the In-Ovation bracket was chosen in its regular form instead of its narrower form (In-Ovation R). Similarly, the Time system was examined both in self-ligating and conventional mode. However, the significance of bracket width for friction is controversial and was considered of secondary importance (Frank and Nikolai, 1980; Drescher *et al.*, 1989).

Pooling conventional and self-ligating brackets also resulted in a mixture of active and passive (Damon 2) clip mechanism in the latter group. Data inspection shows, however, that dropping Damon 2 from this group would increase the mean differences from the conventional group.

Table 4 Statistical summary of friction data for the pooled group of self-ligating and conventionally ligated brackets. The pooled group of self-ligating brackets (n = 80) is composed of Speed, Damon 2, In-Ovation, and Time (self-ligating); the pooled group of conventionally ligated brackets (n = 60) is composed of Victory Twin, Discovery, and Time (conventionally ligated).

Bracket system	Archwire type	Archwire size (inches)	n	Mean (N)	SD (N)	Median (N)	Interquartile range (Q3–Q1, N)	Minimum (N)	Maximum (N)
Self-ligating	Stainless steel	0.017 × 0.025	80	11.5	2.7	11.1	3.6	6.5	21.5
		0.018 × 0.025	80	6.2	2.2	6.1	2.6	2.1	13.8
		0.019 × 0.025	80	12.0	3.6	11.9	4.0	5.3	23.2
Conventional	Stainless steel	0.017 × 0.025	60	9.5	3.1	9.4	3.0	3.6	19.8
		0.018 × 0.025	60	8.2	3.2	7.1	4.5	2.5	20.0
		0.019 × 0.025	60	8.0	2.8	7.9	4.5	2.1	14.1

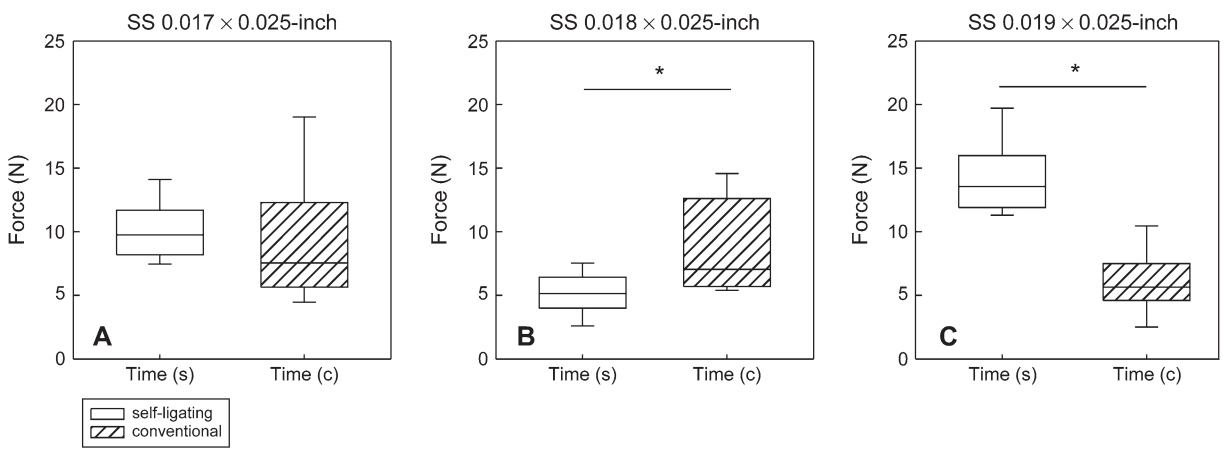

Figure 3 Boxplots showing the maximum frictional forces of the Time self-ligating (s) bracket and the conventionally (c) ligated Time bracket depending on the wire dimensions used: (A) stainless steel (SS) 0.017 × 0.025 inch, (B) SS 0.018 × 0.025 inch, and (C) SS 0.019 × 0.025 inch. *Significant comparisons ($P \leq 0.05$) according to Mann–Whitney's U-test.

To take account of the above-mentioned limitations of pooling groups, significance testing was restricted to pairwise inter-bracket comparisons.

The results showed that the self-ligating brackets had lower frictional values only with 0.018 × 0.025 inch SS wire. With wire dimensions of 0.017 × 0.025 and 0.019 × 0.025 inches, the conventionally ligated brackets showed lower frictional forces than the self-ligating brackets. A number of authors have demonstrated that self-ligating brackets show reduced frictional forces compared with conventionally ligated brackets (Sims *et al.*, 1993; Shivapuja and Berger, 1994; Kapur *et al.*, 1998; Pizzoni *et al.*, 1998; Thomas *et al.*, 1998; Thorstenson and Kusy, 2001; Taylor and Ison, 1996). The present study demonstrates that friction values of self-ligating and conventionally ligated brackets depend mainly on the different wire dimensions. Therefore, information concerning the frictional values of brackets should always consider wire dimensions and testing conditions (e.g. angulation).

Similar experiments (Henao and Kusy, 2004, 2005) demonstrated the effects of alternative wire sizes recommended by the manufacturers. However, compared with the present study those authors used a different experimental method, testing friction in quadrants of typodont models.

Tipping is a constant phenomenon during sliding tooth movements. Thus, teeth will tip until contact is established between the archwire and the diagonally opposite corners of the bracket wings. According to the previously described model for measuring friction, this study, like that of Bednar *et al.* (1991), permitted rotation of the bracket and wire in order to simulate this clinical condition.

Similar to the present experimental set-up, a number of trials included a second-order angulation (Bednar *et al.*, 1991; Sims *et al.*, 1994; Read-Ward *et al.*, 1997; Pizzoni *et al.*, 1998; Thorstenson and Kusy, 2001). According to Pizzoni *et al.* (1998), friction increases with angulation for all bracket/wire combinations. For this reason, the frictional forces found in this study are much higher than, for instance, those reported by Kapur *et al.* (1998), who measured friction without angulation. In the present investigation, torque effects (third-order angulation) were not simulated. Even though torque increases friction in clinical situations, only a few studies simulating this effect are found in literature (Drescher *et al.*, 1991; Bourauel *et al.*, 1992).

The results found by Bednar *et al.* (1991) were mostly confirmed under similar testing conditions. Simulating the clinical situation in which teeth tip slightly while they slide along the archwire, they found that self-ligating steel brackets did not demonstrate less friction than elastic or SS ligated brackets.

The variability of friction among self-ligating brackets is probably due to the different clip mechanisms. While the Speed, In-Ovation, and self-ligating Time bracket feature an active clip mechanism, the Damon 2 bracket has a passive mechanism.

The Time bracket can be used as a self-ligating bracket or as a conventionally ligated bracket, thereby allowing direct comparison of friction. The self-ligating Time bracket showed the largest frictional differences of all self-ligating brackets between the three different wire dimensions. This might be due to the effect of tilting, which is much lower with self-ligating brackets and with smaller wire dimensions. Using the Time bracket as a conventionally ligated bracket with an elastic ligature yielded different frictional forces, showing a smaller range among the different wire dimensions.

In this study, friction was tested under dry conditions. The effect of lubrication by saliva on friction is controversial. Andreasen and Quevedo (1970) claimed that saliva played an insignificant role, while Read-Ward *et al.* (1997) concluded that the presence of human saliva had an inconsistent effect on static friction and sliding mechanics. Baker *et al.* (1987) found that saliva acted as a lubricant, while Stannard *et al.* (1986) and Downing *et al.* (1995) reported that saliva increased friction. Kusy *et al.* (1991) regarded artificial saliva as inadequate for replacement of human saliva and hence such experiments as invalid. Thus, in the present investigation, the wire–bracket couples were tested under dry conditions.

All three conventional metal brackets were ligated with elastomeric modules in this study. Tying with SS ligatures was found to vary both inter- and intraindividually. Since Schumacher *et al.* (1990) reported a considerable variation of pressure between 2 and 8 N with 0.011 inch SS ligatures, elastic ligatures were used in the present study in order to minimize variations and to standardize the ligation process.

Generally, friction appears to increase with archwire diameter (Angolkar *et al.*, 1990), a finding that could not be supported by the results of the present investigation. For nearly all bracket types, the 0.018 × 0.025 inch SS wire produced lower friction than the 0.017 × 0.025 and 0.019 × 0.025 inch wire. Self-ligating brackets combined with a 0.018 × 0.025 inch wire showed a 45–47 per cent reduction in friction compared with wire dimensions of 0.017 × 0.025 and 0.019 × 0.025 inches. With the conventionally ligated brackets, the difference in frictional force between 0.017 × 0.025 and 0.019 × 0.025 inch wires in comparison with 0.018 × 0.025 inch wire was approximately 14 per cent or less. Wire dimension had a lower influence on friction with conventionally ligated brackets than with self-ligating brackets. Therefore, the choice of a bracket system for patient treatment should always consider the correct wire dimension to produce the lowest possible frictional force.

Conclusions

1. Nearly all brackets showed the lowest frictional forces with SS wire with a dimension of 0.018 × 0.025 inches, except the conventionally ligated Time bracket.
2. Friction of the self-ligating brackets was 45–48 per cent lower with 0.018 × 0.025 inch wire compared with 0.017 × 0.025 and 0.019 × 0.025 inch wire. With

conventionally ligated brackets, there was a 14 per cent or less reduction of friction using 0.018 × 0.025 inch wire.

3. Friction of the self-ligating brackets was lower only with 0.018 × 0.025 inch wire. With wire dimensions of 0.017 × 0.025 and 0.019 × 0.025 inches, friction of the conventionally ligated brackets was lower. There was a significant difference ($P < 0.001$) in friction between the self-ligating and conventionally ligated brackets with all wire dimensions. Wire dimension had a strong influence on the friction of self-ligating brackets. With conventionally ligated brackets, wire dimension had a much lower influence.
4. The highest frictional differences were observed with the Time bracket. Friction with the 0.018 × 0.025 inch wire was significantly less ($P < 0.001$) and with 0.019 × 0.025 inch wire significantly greater ($P < 0.001$) than in conventionally ligated brackets.
5. Wire dimension and testing apparatus had an influence on friction measured *in vitro*.

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References

Andreasen G F, Quevedo F R 1970 Evaluation of friction forces in the 0.022 × 0.028 edgewise bracket *in vitro*. Journal of Biomechanics 3: 151–160

Angolkar P V, Kapila S, Duncanson Jr M G, Nanda R S 1990 Evaluation of friction between ceramic brackets and orthodontic wires of four alloys. American Journal of Orthodontics and Dentofacial Orthopedics 98: 499–506

Baker K L, Nieberg L G, Weimer A D, Hanna M 1987 Frictional changes in force values caused by saliva substitution. American Journal of Orthodontics and Dentofacial Orthopedics 91: 316–320

Bednar J R, Gruendeman G W, Sandrik J L 1991 A comparative study of frictional forces between orthodontic brackets and arch wires. American Journal of Orthodontics and Dentofacial Orthopedics 100: 513–522

Bourauel C, Drescher D, Thier M 1992 An experimental apparatus for the simulation of three-dimensional movements in orthodontics. Journal of Biomedical Engineering 14: 371–378

Dickson J A, Jones S P, Davies E H 1994 A comparison of the frictional characteristics of five initial alignment wires and stainless steel brackets at three bracket to wire angulations—an *in vitro* study. British Journal of Orthodontics 21: 15–22

Downing A, McCabe J F, Gordon P H 1995 The effect of artificial saliva on the frictional forces between orthodontic brackets and archwires. British Journal of Orthodontics 22: 41–46

Drescher D, Bourauel C, Schumacher H A 1989 Frictional forces between bracket and arch wire. American Journal of Orthodontics and Dentofacial Orthopedics 96: 397–404

Drescher D, Bourauel C, Thier M 1991 Application of the orthodontic measurement and simulation system (OMSS) in orthodontics. European Journal of Orthodontics 13: 169–178

Frank C A, Nikolai R J 1980 A comparative study of frictional resistances between orthodontic bracket and arch wire. American Journal of Orthodontics 78: 593–609

Henao S P, Kusy R P 2004 Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. Angle Orthodontist 74: 202–211

Henao S P, Kusy R P 2005 Frictional evaluations of dental typodont models using four self-ligating designs and a conventional design. Angle Orthodontist 75: 75–85

Ireland A J, Sherriff M, McDonald F 1991 Effect of bracket and wire composition on frictional forces. European Journal of Orthodontics 13: 322–328

Kapur R, Sinha P K, Nanda R S 1998 Frictional resistance of the Damon SL bracket. Journal of Clinical Orthodontics 32: 485–489

Kusy R P, Whitley J Q, Prewitt M J 1991 Comparison of the frictional coefficients for selected archwire-bracket slot combinations in the dry and wet states. Angle Orthodontist 61: 293–302

Pizzoni L, Ravnholt G, Melsen B 1998 Frictional forces related to self-ligating brackets. European Journal of Orthodontics 20: 283–291

Read-Ward G E, Jones S P, Davies E H 1997 A comparison of self-ligating and conventional orthodontic bracket systems. British Journal of Orthodontics 24: 309–317

Schumacher H A, Bourauel C, Drescher D 1990 Das Friktionsverhalten von Keramikbrackets bei der bogengeführten Zahnbewegung. Fortschritte der Kieferorthopädie 51: 259–265

Shivapuja P K, Berger J 1994 A comparative study of conventional ligation and self-ligation bracket systems. American Journal of Orthodontics and Dentofacial Orthopedics 106: 472–480

Sims A P, Waters N E, Birnie D J, Pethybridge R J 1993 A comparison of the forces required to produce tooth movement *in vitro* using two self-ligating brackets and a pre-adjusted bracket employing two types of ligation. European Journal of Orthodontics 15: 377–385

Sims A P, Waters N E, Birnie D J 1994 A comparison of the forces required to produce tooth movement *ex vivo* through three types of pre-adjusted brackets when subjected to determined tip or torque values. British Journal of Orthodontics 21: 367–373

Stannard J G, Gau J M, Hanna M A 1986 Comparative friction of orthodontic wires under dry and wet conditions. American Journal of Orthodontics 89: 485–491

Taylor N G, Ison K 1996 Frictional resistance between orthodontic brackets and archwires in the buccal segments. Angle Orthodontist 66: 215–222

Thomas S, Sherriff M, Birnie D 1998 A comparative *in vitro* study of the frictional characteristics of two types of self-ligating brackets and two types of pre-adjusted edgewise brackets tied with elastomeric ligatures. European Journal of Orthodontics 20: 589–596

Thorstenson G A, Kusy R P 2001 Resistance to sliding of self-ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (saliva) states. American Journal of Orthodontics and Dentofacial Orthopedics 120: 361–370