The effect of different combinations of tip and torque on archwire/bracket friction

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SUMMARY The aim of this laboratory-based study was to investigate the effects of different combinations of tip and torque upon friction between an orthodontic bracket and archwire using a specially made jig. Victory Twin Series upper premolar brackets (3M Unitek) were mounted on a jig, which allowed tip and torque values in the slot to be varied without altering the centre of rotation. The jig was mounted on an Instron machine and resistance to sliding (RS) was measured as brackets were drawn along rectangular 0.019×0.025 inch wires at various combinations of tip and torque from 0 to 12 degrees. Five tests were carried out for each combination. The results were analysed using analysis of variance and Tukey's pairwise comparisons by means of the Minitab statistical package.

Increasing tip and torque produced increases in sliding resistance from 1.35 to 19.08 N. Both tip and torque had significant effects on friction. RS was significantly increased by tip and torque separately (P < 0.001) and in combination (P < 0.001), although tip was the more powerful influence.

Introduction

The laws of friction were derived from the straight-line sliding of materials in the dry state and there are three basic principles: friction is proportional to the force acting at right angles to the contact and it is independent of both contact area and sliding velocity (Tidy, 1989; O'Reilly *et al.*, 1999). The coefficient of friction of a material is a constant, which depends upon surface roughness, texture, and hardness.

Friction is determined in two ways. Static friction is the smallest force needed to start movement while kinetic friction is the force that resists the sliding motion of one solid object over another at a constant speed (Omana *et al.*, 1992). According to the laws of physics, static friction is always greater than kinetic friction (Kapila *et al.*, 1990; Nanda and Ghosh, 1997) but the situation is more complicated when brackets are moved along an orthodontic wire in the mouth since teeth move in a series of short jumps (Read-Ward *et al.*, 1997). The ease with which brackets slide along an archwire is influenced by the wire material, its cross-sectional size and shape, the material and design of the brackets, and the ligation method (Nanda and Ghosh, 1997).

The proportion of applied force that is translated into tooth movement decreases as friction increases so that the force required to overcome friction may be up to 60 per cent (Drescher *et al.*, 1989) or half of the total force applied to a bracket (Kusy *et al.*, 1997; Proffit and Fields, 2000). The sequence of archwires chosen may have a profound effect on the amount of friction generated between brackets and archwires.

It is therefore evident that the management of friction is an important consideration in orthodontics, although there have

been few attempts to measure the actual forces involved. There is, however, an appreciation that reducing the causes of resistance to the sliding of fixed appliance attachments will shorten chairside treatment time (Articolo and Kusy, 1999), and orthodontic treatment is facilitated if both static and kinetic friction are minimized (Proffit and Fields, 2000).

The resistance to sliding (RS) of orthodontic brackets has three components: classical friction, binding, and notching of the wire (Kusy and Whitley, 1997). In situations where the contact angle θ is below the critical value, only classical friction is important because binding (Frank and Nikolai, 1980; Kapila *et al.*, 1990) and notching (Articolo *et al.*, 2000) do not occur. It has been suggested that notching is produced due to vertical movements of the teeth or wire during mastication (Articolo *et al.*, 2000). The effect of notching upon RS was not investigated in the present study since it would be difficult to replicate the effects of repeated masticatory movement in the laboratory and since notching appears to be associated particularly with the use of ceramic brackets (Articolo *et al.*, 2000).

The three geometric parameters of importance in determining binding for an individual bracket are the relative size of the wire, the bracket slot, and the width of the bracket (Figure 1). In the present study, brackets were measured using a micrometer and found to be 0.126 inches across the tie wings. For a true 0.019×0.025 inch wire in a 0.022 inch slot, the critical angle at which binding would begin with regards to bracket tip can be calculated using the formula:

$$\tan \theta \operatorname{tip} = \frac{\operatorname{Slot size-archwire height}}{\operatorname{Bracket width}} = \frac{0.003}{0.126} = 0.0238.$$

Therefore θ tip = 1 degree.



Figure 1 Schematic representation of the critical angle for binding with respect to tip for a 0.019×0.025 inch wire in a bracket with a 0.022 inch slot.



Figure 2 The jig in place on the Instron.

The critical angle for binding in relation to wire twist or torque is calculated as:

$$\tan \theta$$
 torque = $\frac{\text{Slot size} - \text{archwire height}}{\text{Archwire width}} = \frac{0.003}{0.025} = 0.12.$

Therefore θ torque = 7 degrees.

The above calculations are not completely accurate since the corners of square and rectangular orthodontic wires are not square but bevelled (Hixson *et al.*, 1982). The effects on sliding resistance of wire configurations above the critical angle for binding have been little studied due to the experimental difficulties associated with accurate measurement of bracket angulation (Kusy and Whitley, 1999). The same authors therefore used linear regression to derive the critical binding angles for a range of wire sizes and bracket widths. Their calculations did not extend to consideration of the third order or torque plane.

The aim of the present study was to measure the effects of various combinations of tip and torque on the static friction between preadjusted brackets and rectangular stainless steel archwires using a specially made jig. This work follows that of Sims *et al.* (1994) and Moore *et al.* (2004) using a newly designed jig to introduce different combinations of tip and torque into the bracket–archwire interface.

Materials and methods

A jig that could be clamped to an Instron machine (Model 5544, Instron Ltd, High Wycombe, Buckinghamshire, UK) was constructed to introduce tip and torque in 1 degree increments at the bracket slot of an upper premolar bracket (Figure 2). The jig was developed from experience gained using a previous jig (Moore *et al.*, 2004).

All tests were carried out using straight lengths of 0.019 \times 0.025 inch rectangular stainless steel archwire (Standard Rectangular Wire, 3M Unitek, Bracknell, Berkshire, UK). Victory Twin Series upper premolar brackets (3M Unitek) were mounted on brass stubs using 0.0215 \times 0.025 inch wire which fitted the bracket slot closely so that the procedure was as accurate as possible. The wires were measured using a micrometre (Model 1961 MB, Moore and Wright, Sheffield, UK) and found to conform to their nominal sizes. Examination under a stereomicroscope at \times 20 magnification showed that the corners of the wires were not bevelled as suggested by Hixson *et al.* (1982) but rounded.

The basic components of the jig were firstly a square section hollow brass tube (dimensions outside 10 mm and inside 7 mm) supported by a buttress to provide rigidity. A section of one face of the tube was cut out to create a slot into which were fitted two brass blocks. The lower block was fixed by means of a grub screw through the brass tube but the upper block was able to slide within the lumen of the tube, its position being set by adjusting a spring loaded screw thread, which passed through the block. A 0.0215 \times 0.026 inch slot was machined into the face of each block and closed by means of a soldered brass 'lid'. The whole assembly was fixed to the baseplate of the jig by means of a screw that was in line with the bracket slot, around which it could be turned to introduce twist (torque) into a test archwire mounted through the slots in the brass blocks. Torque was set by means of a pin through calibrated holes in the brass base of the rod and the aluminium plate on which it was mounted (Figure 2). The length of a test wire was set at 18.4 mm to represent the clinical wire span between the distal side of a canine bracket and the mesial end of a first molar tube, using tooth sizes according to Ash (1993) and bracket dimensions as measured using a micrometer (Figure 3). When mounting a test wire, the distance between the blocks



Figure 3 Diagram showing calculation of the archwire span.



Figure 4 Close-up showing the hinged rod during bracket mounting.

was first set to 18.4 mm. A straight length of 0.019×0.025 inch wire was then passed through the slots and turned over at right angles at each end. The wire was then tensioned to 300 g by means of the screw above the tension spring as recommended by Kapila *et al.* (1990). This was undertaken to ensure that all test wires were straight and under equal amounts of tension.

The second main component of the jig was a 7 mm square brass rod mounted on the base of the jig parallel to the tube described above at a distance of 2 cm. The base of the rod was hinged so that it could be swung through 90 degrees away from the tube to facilitate bracket mounting (Figure 4). The brass rod carried a slide, to which was

attached a brass plate with holes at 1 degree intervals. Over this was a pointer, which was moved across the plate to set the tip in a bracket mounted on a removable square stub at its base.

Each bracket was 0.126 inches (3.2 mm) in width across the tie wings and the slot size was 0.022×0.026 inches with 0 degrees of tip and 7 degrees of palatal torque.

A length of full-size 0.0215×0.025 inch stainless steel wire was fixed into position between the blocks and a bracket was attached to it by means of an elastic module. A small amount of Transbond XT light cure adhesive paste (3M Unitek) was placed onto the end of the mounting stub and the hinged rod was brought to the vertical so that the composite on the mounting stub united with that on the base of the adhesive pre-coated bracket (3M Unitek). The bracket was positioned to lie in the centre of the mounting rod and the composite was then cured by light activation for 20 seconds on either side of the bracket using a curing light (3M Unitek). Before testing began, six brackets were mounted in this way.

Friction was measured by pulling a bracket along the wire using a loop of 0.09 mm round stainless steel wire clamped to the upper crosshead of the Instron testing machine, with the jig bolted to the lower crosshead. With the loop passed under the bracket tie wings, the crosshead was moved up at 10 mm/minute (Tselepsis et al., 1994; Articolo and Kusy, 1999; Kusy and O'Grady, 2000). Firstly, the bracket was positioned at the bottom of the wire and the wire loop was raised until the loop just touched the bracket so that a reading registered on the Instron dial. The cross head was then moved up by 3.7 mm to represent the distance between the distal edge of an upper second premolar bracket and the mesial edge of a first molar tube. Tip and torque values were then set and the Instron recalibrated to zero to account for the weight of the slide assembly. Maximum friction was recorded over a wire span of 11 mm so that the final position of the bracket was 3.7 mm from the upper block, to represent the distance between the mesial edge of an upper second premolar bracket and the distal edge of a canine bracket. Tip and torque were then reset to zero, the crosshead of the Instron was returned to its starting position, and a new module was fitted in preparation for the next test for which tip and torque were reset to the correct test values.

Following preliminary testing to ensure that the apparatus worked reliably, six brackets were mounted on stubs and tested at 2 degrees of tip and 2 degrees of torque using 0.019×0.025 inch wires. Four brackets gave similar friction values but readings for the other two were just outside the confidence limits. These two brackets were therefore discarded.

A separate series of five tests was carried out for each combination of tip and torque values between 0 and 12 degrees, a total of 80 individual tests. A new 0.019×0.025 inch archwire was fitted before each series of five tests and the bracket was changed by a system of random allocation to one of the four calibrated brackets before each series.

Based on the work of Frank and Nikolai (1980), friction was measured for 16 combinations of tip and torque in increments of 4 degrees from 0 to 12 degrees using 0.019×0.025 inch wires.

The results were analysed using analysis of variance (ANOVA) and Tukey's pairwise comparisons using the Minitab statistical package (Minitab Ltd, Coventry, Warwickshire, UK).

Results

The Instron trace did not register a reading when the apparatus was tested with a mounted bracket but no archwire, demonstrating that the system was virtually friction free.

Frictional measurements for different combinations of tip and torque from 0 to 12 degrees ranged from 1.35 to 19.08 N (Table 1). One-way ANOVA confirmed that increases in tip and torque produced highly significant changes in sliding resistance, F = 489.56, P < 0.001. Cross tabulation of the results using Tukey's pairwise comparisons showed statistically significant differences in 100 (85 per cent) of 117 cells, revealing the effect of any increase in either tip or torque (Table 2).

Every 4 degree increase in tip produced significant increases in friction (Table 3) F = 1869.92, P < 0.001. Cross tabulation of the result for tip alone showed that each 4 degree increase in tip produced a significant increase in sliding resistance.

The effect of increases in torque alone from 0 to 12 degrees is shown in Table 4 (F = 56.62, P < 0.001). Increasing torque from 4 to 8 degrees did not produce a significant increase in sliding resistance, P > 0.05, but increases in all other cells of the cross tabulation were significant.

 Table 1
 Summary results for maximum friction (N) in relation to combinations of tip and torque setting between 0 and 12 degrees in ascending order of magnitude.

Group	Jig so	ettings (°)		Maximum friction (N)			
	Tip	Torque	Mean	Standard deviation	Minimum	Maximum	
1	0	0	1.35	0.21	1.04	1.54	
2	Õ	4	1.92	0.05	1.74	2.03	
3	0	8	2.34	0.09	2.04	2.55	
4	0	12	3.44	0.42	2.87	3.89	
5	4	0	3.44	0.20	3.21	3.74	
6	4	4	3.53	0.25	3.20	3.91	
7	4	8	3.55	0.20	3.32	3.74	
8	4	12	5.30	0.35	4.87	5.83	
9	8	0	8.62	0.31	8.15	8.86	
10	8	4	8.64	0.42	8.16	9.21	
11	8	8	9.02	0.87	8.25	10.43	
12	12	0	11.01	0.19	10.82	11.24	
13	12	4	11.94	0.33	11.65	12.44	
14	12	8	12.79	0.72	11.88	13.89	
15	8	12	13.59	0.71	12.85	14.43	
16	12	12	19.08	1.27	17.65	21.08	

One-way analysis of variance, F = 489.56, P < 0.001.

Discussion

It is difficult, perhaps impossible, to design a laboratory system that fully simulates the friction encountered by brackets and archwires in the mouth, since biological variations will influence responses to force (Iwasaki *et al.*, 2000). The effect of salivary lubrication was not studied in the present *in vivo* investigation since previous work has indicated that saliva exerts a negligible effect on friction (Andreason and Quevedo, 1970). However, further work to determine the effect of tip and torque on sliding mechanics is certainly warranted (Sims *et al.*, 1994). In particular, the relative rankings of archwires and brackets are more meaningful than the actual force values recorded in a given experimental set-up (Tselepsis *et al.*, 1994).

As mentioned in the introduction and according to the laws of physics, kinetic friction cannot exceed static friction. However, other effects play a part in the RS of an orthodontic bracket (Kusy and Whitley, 1997) and this is illustrated by a typical trace taken from the Instron machine, which shows that friction does increase after the initial peak (Figure 5). Sliding resistance was therefore recorded as the highest force (N) recorded by the Instron as a bracket was pulled for 11 mm along a test length of archwire to simulate closure of a premolar extraction space.

The test jig used in the present study was designed so that tip and torque could be incorporated accurately by changing the position of a bracket in two planes. Each archwire was held under a tension of 300 g in order to reduce unwanted twisting and bending of the wire as a bracket was pulled

	0/0	0/4	0/9	0/12	4/0	4/4	1/0	4/12	8/0	0/1	0 /0	12/0	12/4	12/0	0/12	12/12
	0/0	0/4	0/8	0/12	4/0	4/4	4/8	4/12	8/0	0/4	0/0	12/0	12/4	12/8	0/12	12/12
0/4	×															
0/8	×	×														
0/12	\checkmark	~	×													
4/0	~	\checkmark	×	×												
4/4	~	~	\checkmark	×	×											
4/8	\checkmark	\checkmark	\checkmark	×	×	×										
4/12	\checkmark															
8/0	\checkmark	\checkmark	\checkmark	\checkmark	✓	\checkmark	\checkmark	\checkmark								
8/4	✓	\checkmark	\checkmark	\checkmark	✓	~	\checkmark	✓	\checkmark	×						
8/8	\checkmark	\checkmark	\checkmark	\checkmark	✓	✓	\checkmark	\checkmark	×	×						
12/0	✓	\checkmark	\checkmark	\checkmark	✓	✓	\checkmark	\checkmark	~	\checkmark	~					
12/4	✓	\checkmark	\checkmark	\checkmark	✓	✓	\checkmark	\checkmark	~	\checkmark	~	×				
12/8	\checkmark	\checkmark	\checkmark	\checkmark	✓	✓	\checkmark	\checkmark	~	\checkmark	\checkmark	\checkmark	×			
8/12	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	✓	\checkmark	×								
12/12	\checkmark	\checkmark	\checkmark	~	\checkmark	\checkmark	\checkmark	~	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark		

 Table 2
 Cross tabulation of results according to Tukey's pairwise comparisons.

✓, difference significant; ×, difference not significant.

 Table 3
 The effect of increases in tip alone on sliding resistance.

Group	Jig se	ettings (°)	Maximum friction (N)					
	Tip	Torque	Mean	Standard deviation	Minimum	Maximum		
1	0	0	1.35	0.21	1.04	1.54		
5	4	0	3.44	0.20	3.21	3.74		
9	8	0	8.62	0.31	8.15	8.86		
12	12	0	11.01	0.19	10.82	11.24		

One-way analysis of variance, F = 1869.92, P < 0.001.

 Table 4
 The effect of increases in torque alone on sliding resistance.

Group	Jig se	ettings (°)		Maximum friction (N)				
	Tip	Torque	Mean	Standard deviation	Minimum	iimum Maximum		
1	0	0	1.35	0.21	1.04	1.54		
2	0	4	1.92	0.05	1.74	2.03		
3	0	8	2.34	0.09	2.04	2.55		
4	0	12	3.44	0.42	2.87	3.89		

One-way analysis of variance, F = 56.62, P < 0.001.

along (Kapila *et al.*, 1990; Kapur *et al.*, 1999). Combinations of tip and torque were tested in 4 degree increments to a maximum of 12 degrees each. Further increases of tip produced such high forces that the brackets debonded. Permanent deformation of the archwire also became a concern. A preliminary series of tests indicated that the results were not affected by repeated use of the same bracket, but calibrated brackets were rotated through the test groups



Figure 5 A trace produced by the Instron machine.

as a further safeguard against the possible influence of bracket wear (Frank and Nikolai, 1980). The archwire was replaced after every five tests as previously recommended (Kusy and O'Grady, 2000).

The finding that increases in bracket tip significantly increased friction agrees with a number of other studies (Frank and Nikolai, 1980; Peterson *et al.*, 1982; Tidy, 1989; Tselepsis *et al.*, 1994; Kusy and O'Grady, 2000; Loftus and Årtun, 2001).

Each 4 degree increase in bracket tip produced a significant increase in friction, which was to be expected since the critical angle for binding was only 1 degree of tip. Articolo and Kusy (1999) and Thorstenson and Kusy (2002) also found increases in sliding resistance in association with the critical angle and it appears unlikely that such levels of friction would be overcome by a force of 4–6 ounces (1.6 N) that has been recommended for use in clinical orthodontics (Graber and Vanardsdall, 1994). Other effects, such as small tooth movements produced by occlusion, may act to overcome the friction lock in the mouth. If this is so, the elasticity of the periodontal ligament must play an important part. The critical tip angle θ for binding was only 1 degree and the distance of the bracket slot from the apex of a central

incisor would be around 18 mm. The deflection of the apex produced by full expression of the binding angle due to the archwire/bracket couple is therefore given by $\tan \theta \times 18 =$ $0.024 \times 18 = 0.43$ mm, which exceeds the normal width of the periodontal ligament (Palmer, 1999) so that binding of the bracket must occur in the mouth.

The introduction of up to 12 degrees of torque alone produced significant increases in friction (P < 0.001) although the increases were less than for tip alone. The critical angle θ for torque is 7 degrees and this value was exceeded by 8 and 12 degrees jig settings. However, even at the 12 degree setting, which is almost twice the critical angle, the mean RS mean value was only 3.44 N. Twelve degrees of tip alone, without torque, produced a mean RS of 11.01 N.

In combination, both tip and torque were found to have a significant influence on friction. There have been no previous reports of the combined effects of tip and torque. Indeed doubts have been expressed as to whether combined tip and torque values could be incorporated accurately within a test apparatus (Sims et al., 1994) and mathematical formulae have been used to investigate the relationship between torque values and the critical angle for binding (Kang et al., 2003). The test jig devised for the present study was machined to ensure that both tip and torque could be introduced without affecting the centre of rotation of the bracket. A full thickness 0.0215 \times 0.025 inch archwire was used during bracket cementation to ensure correct alignment and the removal of all tip and torque. The finding that tip and torque in combination exert significant effects on friction in a non-linear fashion supports theoretical and computer-aided design work which suggested that torque would be a significant factor in association with tip and that torque angle should be included in evaluating the angle of tip that would be critical to the increase of friction.

The other interpretation that might be placed on the present results is that increasing tip at the bracket slot reduces play so that torque expression is increased (Meling and Odegaard, 1998).

In the early stages of treatment, with small, flexible archwires elastic, binding contributes to sliding resistance (Thorstenson and Kusy, 2002) and this effect may increase resistance 100-fold when bracket angulation is considerably more than the critical angle at which binding begins (Articolo and Kusy, 1999). High angles of tip may produce notching of the archwire, although notching has been observed only at angulations above 9 degrees (Articolo *et al.*, 2000). At angles of torque of 10 degrees and above, permanent deformation of brackets has been reported *in vitro* (McKnight *et al.*, 1994), although it seems doubtful that sufficiently high degrees of torque and the consequent forces would be encountered *in vivo*.

The critical angles for both bracket tip and torque would be changed by alterations in wire size and of the dimensions of the bracket slot. These effects were not investigated in the present study, which tested only the commonly used 0.019 \times 0.025 inch rectangular stainless steel working archwire.

Conclusions

- 1. Resistance to bracket sliding increases significantly as bracket tip increases (P < 0.001).
- 2. RS also increases with increasing torque in the absence of tip (P < 0.001), although the increases are less than those associated with similar amounts of tip.
- 3. The results support the view that steel working arches should be left for a time before elastic traction is applied, in order to allow for tip and torque to be reduced or eliminated by adjustments in the position of a bracket on the archwire (Bennett and McLaughlin, 1993; Sims *et al.*, 1994).

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