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Archwire seating forces produced by different ligation methods and their effect on frictional resistance

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SUMMARY The aims of this study were to determine the mean tensile force of four different elastomeric modules, the archwire seating force of different ligation methods, and its effect on frictional resistance.

To determine the mean tensile force, each elastomeric module (purple, grey, Alastik, and SuperSlick) was extended by 5 mm using two hooks attached to a load cell using a Nene M3000 testing machine. To assess the median archwire seating force, a maxillary premolar bracket (3M Unitek) was welded to a sheet of stainless steel (SS) and glued to a Perspex block. The bracket base was removed and the cut continued into the Perspex below. A length of test wire was taken and bent to form a 'U' shape, with the middle portion 20 mm in length. The free ends of the wire were secured to the load cell of the Nene testing machine. Two wire sizes were tested, 0.017 × 0.025 and 0.019 × 0.025 inch SS. The load cell was activated and the force with which the wire was displaced into the slot by the ligation method was measured. Four types of elastomeric module were tested together with a pre-formed 0.09 inch SS ligature. The experimental method used to determine the mean frictional force of each module and wire size was carried out using a method described previously.

Statistically significant differences existed in the mean tensile forces and median archwire seating forces between the elastomeric modules. Grey modules with either size wire produced the lowest median archwire seating force, whereas SS ligatures produced the highest forces. SS ligatures with either wire produced the lowest mean frictional forces, whereas grey modules produced significantly higher mean frictional force ($P < 0.01$). The force with which the wire was seated into the bracket did not seem to be related to the subsequent amount of mean frictional force produced.

Introduction

Friction is defined as the resistance to motion when one object moves tangentially against another (Benancon, 1985). The frictional force is a product of the coefficient of friction and a force acting perpendicular to the contacting surfaces (Giancoli, 1980). This perpendicularly acting force, in terms of classical physical laws of friction, is referred to as the 'normal force'.

Bracket material, width, interbracket distance (Frank and Nikolai, 1980) and wear of the wire (Keith *et al.*, 1994) are believed to influence frictional resistance. Archwire material (Kapila *et al.*, 1990), diameter, cross-sectional shape (Peterson *et al.*, 1982; Tanne *et al.*, 1991), wire stiffness (Prososki *et al.*, 1991) and active torque (Tidy, 1989) are further factors contributing to friction. Bracket/wire angulation (Dickson *et al.*, 1994), surface roughness of the wire (Kusy *et al.*, 1988), sliding velocity (Kusy and Whitely, 1989), saliva (Kusy *et al.*, 1991) and method of ligation (Sims *et al.*, 1993) also affect frictional resistance.

Few studies have investigated the interaction between the physical characteristics of the ligation method and frictional forces. Dowling *et al.* (1998) and Lam *et al.* (2002) investigated the 'failure load forces' or tensile strength of different types of elastomeric module. The tensile strength exhibited by six differently coloured elastomeric modules, manufactured by 3M Unitek, ranged from 20.4 to 21.8 N, over an extension range of 8.3–10.0 mm (Lam *et al.*, 2002). It seems that no study has investigated the tensile force/extension characteristics of an elastomeric module prior to failure.

Previous studies appear to assume that the archwire seating force generated by an elastomeric module is identical for each module type. A recent study attempted to quantify the archwire seating forces by a combination of direct measurement and theoretical mathematical calculation (Iwasaki *et al.*, 2003). The overall mean archwire seating force values for the tight stainless steel (SS) ligation samples and the loose SS ligation samples were 14.7 ± 9.2 and 6.2 ± 5.8 N, respectively. The mean archwire seating force was found to be 16.0 ± 1.7 N for the elastomeric modules. The study also showed that consistent archwire seating forces were difficult to achieve with SS ligatures, even by a trained operator.

The lack of reproducibility of archwire seating forces between ligation methods has previously been discussed in the literature and has been shown to range from 50 to 300 g (Nanda, 1997). Attempts have been made to standardize the archwire seating force (Articolo and

Kusy, 1999). That study showed that friction increases proportionally as the archwire seating force increases with a SS ligature. The investigators chose an arbitrary archwire seating force of 300 g (3.0 N) for further investigations, but no justification for this value was given (Kusy and Whitley, 2000). No previous published studies have attempted to determine the archwire seating force by direct measurement.

The aims of this investigation were first to determine the tensile characteristics of four different elastomeric modules: purple, grey, Alastik (3M Unitek, Monrovia, California, USA) and SuperSlick (TP Orthodontics, La Porte, Indiana, USA). Second, to determine the archwire seating forces generated by different ligation methods, elastomeric and SS, and finally to determine the relationship between archwire seating forces and frictional resistance.

Materials and methods

Tensile force of elastomeric modules

A testing machine (Nene M3000, Wellingborough, Northamptonshire, UK) with a 5 kg load cell was used for this study. A piece of 1.0 mm diameter wire, 15 mm in length, was secured to the lower fixed clamp of the Nene testing machine. A second identical piece of wire was secured to the clamp attached to the load cell so that it was parallel to the first wire and separated by 5 mm. The elastomeric modules were placed over the ends of the wire with a ligature gun (Straight-shooter, TP Orthodontics). This ensured that each module was stretched by a standard amount prior to placement (Bazakidou *et al.*, 1997). Whole, unstimulated, saliva was dripped onto each module at a rate of 1 ml/minute from a plastic syringe (Plastipak, Westons Internet, Hassocks, West Sussex, UK). The load cell recorded the force with which the module was being stretched. The DC analogue voltage produced was passed through a data acquisition board and interpreted by software (Nene) on a personal computer (Elonex, London, UK). The data were then stored and exported as an ASCII file. This file type was then imported into Excel (Microsoft® Excel 2000, Microsoft Corporation, USA) for analysis.

Archwire seating force

A maxillary premolar bracket with a 0.022 inch slot dimension and 0 degree tip and torque (3M Unitek) was welded to a sheet of SS measuring 10 × 10 mm. This was then glued to a Perspex block with epoxy resin (Araldite, Bostik Ltd, Leicester, UK). The bracket was orientated with the long axis of the slot in a sagittal direction and at right angles to the direction of measurement of the load cell (Figure 1). The Perspex block was secured to the top of the rack and pinion mechanism, with a screw passing through its base. Turning the dial moved the block in a sagittal direction. This was then secured to the lower fixed clamp of the Nene testing machine.

A straight 100 mm length of 0.019 × 0.025 inch SS wire (3M Unitek) was taken and bent to form a ‘U’ shape. The middle portion of the wire was 20 mm long while the free ends were each 40 mm in length. The wire was examined visually using torquing pliers (3M Unitek) to ensure that this procedure had not introduced any torque into the wire. Wire in which torque was introduced was discarded. The wire was secured to the load cell, so that the 20 mm length of wire was parallel to, and overlying, the bracket slot.

A multimeter (Micronta Digital Multimeter, Maplin Electronic Ltd, Barnsley, West Yorkshire, UK), which measures resistance, was connected with one lead attached to the bracket and the other to the test wire. The crosshead was lowered until contact was made between the base of the wire and the top of the bracket slot. At this point, the multimeter read a complete circuit and the crosshead was stopped. The dial on the lower mechanism was turned, which moved the bracket sagittally along the wire until it was totally free of the wire. The Perspex block was then unscrewed from the mechanism. Using a diamond-cutting disc, the bracket base was removed and a groove made in the Perspex below the slot. The block was then reattached to the lower mechanism and the dial adjusted to place the block in its original position, underneath the wire. The crosshead was stationary while the load cell was activated; this allowed the load cell to measure the force with which the wire was being displaced into the slot. Each wire type was tested 10 times using each type of module.

Two different sizes of orthodontic wire, 0.017 × 0.025 and 0.019 × 0.025 inch, were used in this study. In total, 100 specimens were tested. The bracket and wire were ligated with either one of four types of elastomeric module, purple, grey, Alastik (3M Unitek) or SuperSlick (TP Orthodontics), or by a pre-formed 0.09 inch SS ligature (3M Unitek).

Each elastomeric module was placed over the tie wings of the bracket with a ligature gun. In an attempt to standardize SS ligature placement, a previously described technique was used (Bazakidou *et al.*, 1997). Each short ligature, once placed ready for tightening, was given seven full turns of the Spencer-Wells clips. Prior to placing the clips, a right angle bend was made in the pre-twisted portion of the short ligature to prevent the clips from slipping on the ligature. The clip was then removed and the wire left horizontal and parallel to the wire.

The tests were conducted using fresh, whole human saliva obtained without stimulation. Saliva was dripped onto the bracket–wire junction at a rate of 1 ml/minute from a plastic syringe. All tests were conducted at a room temperature of 25°C. All archwires and brackets were washed in 95 per cent ethanol and air-dried prior to testing. The load

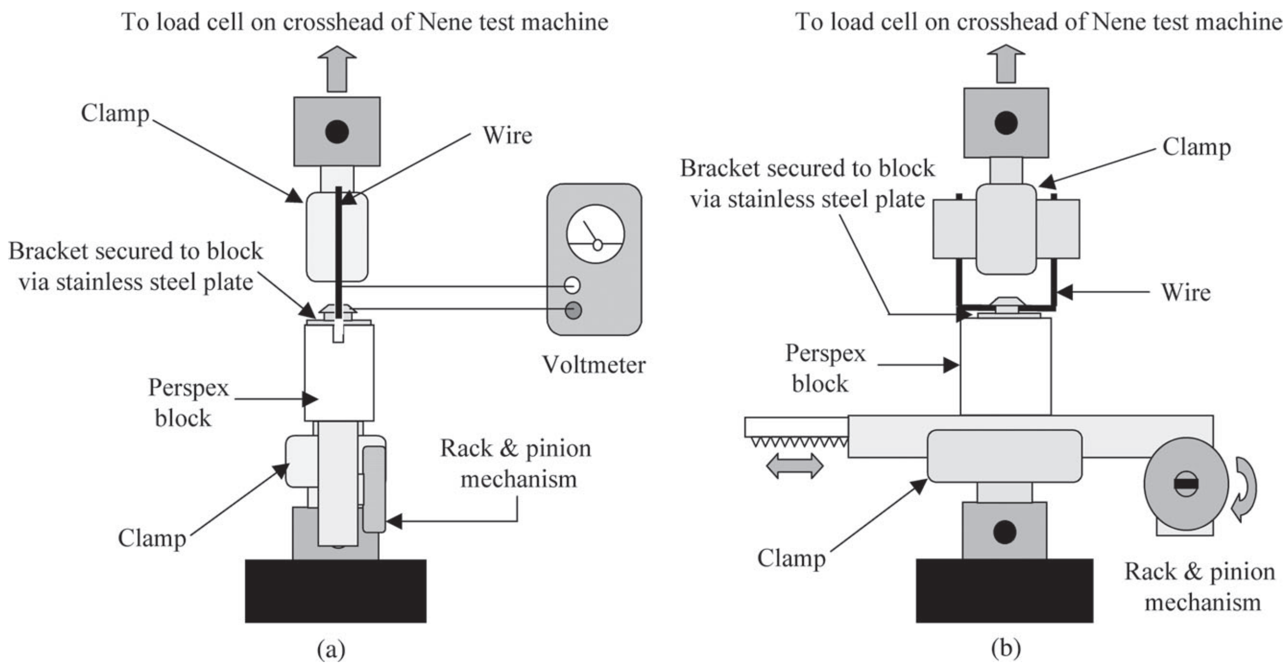

Figure 1 Diagrammatic representation of the experimental set-up: (a) side view and (b) front view (syringe not shown).

cell recorded the force with which the module pushed the wire into the bracket slot. The data were then stored and exported as described previously.

Frictional resistance

A Perspex block was secured to the top of the rack and pinion mechanism, so that turning the dial would move the block in a sagittal direction. A 20 mm length of orthodontic tubing, with a 0.8 mm internal diameter, was secured to the block with self-cure acrylic resin (Orthoresin, Dentsply Ltd, Surrey, UK). The short end of the test wire (10 mm) was inserted into the tubing and the dial turned to allow the now vertical portion of wire to engage the bracket slot passively. The passivity of the wire–bracket engagement was checked by gently rotating the dial backwards and forwards to ensure that the wire moved freely within the bracket slot. Any adjustments to the block carrying the bracket or the wire could be made to remove any binding. All archwires and brackets were washed in 95 per cent ethanol and air-dried prior to testing. The tests were conducted in the presence of fresh, whole human saliva obtained without stimulation. Saliva was dripped onto the bracket–wire junction at a rate of 1 ml/minute from a syringe. The crosshead speed was set to 5 mm/minute and each test run lasted for 4 minutes. Each bracket and archwire combination was only tested once to eliminate the influence of wear. The load cell recorded the force values needed to move the wire through the bracket, i.e. the resistance to sliding. The data were then stored and exported as described previously.

Data analysis

Tensile force of elastomeric modules and frictional resistance.

After checking that the data were normally distributed, a one-way analysis of variance (ANOVA) was used to determine whether the mean tensile forces of the four elastomeric modules were equal. The same statistical test was used to determine whether the mean frictional forces of the five ligation groups, for each of the two wire sizes, in turn were equal. Suitable follow-up multiple comparisons were used to identify between which groups there were significant differences.

Archwire seating force.

As the archwire seating force data were not normally distributed, a Kruskal–Wallis test was used to determine whether the median archwire seating forces of the five ligation groups were equal, for each of the wire sizes separately. Suitable follow-up multiple comparisons were used to identify between which of the ligations there were significant differences. A Mann–Whitney test was used to determine the effect of archwire size on median archwire seating force, for each of the five ligation methods.

Results

Tensile force of elastomeric modules

Significant differences in mean tensile force were observed between the four module types. There was, however, no significant difference between the mean tensile force of the purple and grey modules. There was also no significant difference between the SuperSlick and Alastik modules. All other pairwise comparisons of module types were significantly different, after adjusting for multiple comparisons (Table 1).

Archwire seating force

Figure 2 shows boxplots of the archwire seating force for each of the five ligation methods used with the two wire sizes. The boxplot identifies the middle 50 per cent of the data, the median, and the extreme points. There was large variability across the methods of ligation, particularly with the SS ligature, which makes it difficult to identify any potential significant differences. It also means that applying a two-way ANOVA, with factors of wire size and ligation method, is inappropriate, and thus the data for each wire size were considered separately.

Table 2 shows the median archwire seating force for each module type and wire size combination. For each of the wire sizes separately, the test of equality of median archwire seating force of the five ligations gave a value of $P < 0.001$, indicating significant differences in median archwire seating force between the five ligation methods.

Table 1 Mean tensile forces (standard deviation) for each module type.

Order of tensile forces in terms of means (standard deviation) (N) Smallest force → largest force			
Grey[a]	Purple[a]	SuperSlick[b]	Alastik[b]
1.3 (0.02)	1.3 (0.03)	1.6 (0.02)	1.7 (0.02)

Common symbol, no significant difference between ligations; different symbol, significant difference between ligations.

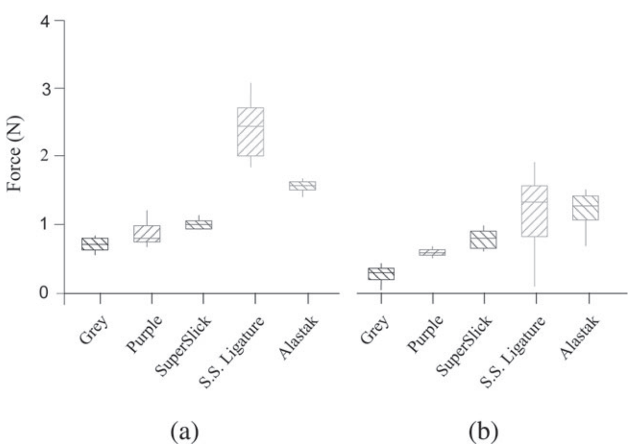

Figure 2 Boxplots for median archwire seating force by method of ligation for (a) 0.017 × 0.025 and (b) 0.019 × 0.025 inch stainless steel wire.

Follow-up multiple comparisons identified significant differences between each of the ligation methods.

0.017 × 0.025 inch SS.

For 0.017 × 0.025 inch SS, grey modules gave the lowest median archwire seating force, which was significantly lower than the purple modules, which in turn was significantly lower than the SuperSlick modules. The median archwire seating forces for the SuperSlick modules and SS ligatures were not significantly different, and there was no significant difference between the SS ligatures and Alastik modules (Figure 2).

0.019 × 0.025 inch SS.

Again, the lowest median archwire seating force was for the grey module group, but there was no significant difference between the grey and purple modules, or between the purple and SuperSlick modules. However, both Alastik modules and SS ligatures had significantly higher median archwire seating forces than any of the other ligation methods, and were also significantly different from each other (Figure 2).

0.017 × 0.025 inch versus 0.019 × 0.025 inch SS.

When the two wire sizes were compared for each of the five ligation methods, the median archwire seating force with the 0.019 × 0.025 inch wire was significantly greater than the median archwire seating force for the 0.017 × 0.025 inch wire (all $P < 0.01$).

Mean frictional resistance

Table 3 gives the mean frictional force of each of the five ligations for each of the wire size combinations. For each of these combinations, the test of equality of means of the five ligations gave a value of $P < 0.01$, suggesting that there is evidence of significant differences in mean frictional force between the five ligation groups.

0.017 × 0.025 inch SS.

SS ligatures gave the smallest mean frictional force, which was significantly lower than the mean force for the grey, SuperSlick or Alastik modules, but not significantly different from the purple module. The mean force for the Alastik module was significantly higher than for three of the other four methods of ligation (Figure 3).

0.019 × 0.025 inch SS.

The lowest mean frictional force was recorded with the SS ligature, which was significantly lower than that of the grey and SuperSlick modules, but not significantly different from the mean frictional forces of the Alastik and purple

Table 2 Median archwire seating forces (range) for each module type and wire size combination.

Size	Order of ligation in terms of median (range) archwire seating force (N) Smallest force → largest force			
0.017 × 0.025 inch	Grey[a] 1.3 (1.0–1.4)	Purple[b] 1.6 (1.3–1.8)	SuperSlick[c] 1.8 (1.6–2.0)	SS ligature[cd] 2.3 (1.0–2.9)	Alastik[d] 2.3 (1.7–2.5)
0.019 × 0.025 inch	Grey[a] 1.7 (1.6–1.8)	Purple[ab] 1.8 (1.7–2.2)	SuperSlick[b] 2.0 (1.9–2.1)	Alastik[c] 2.6 (2.2–2.7)	SS ligature[d] 3.5 (2.9–4.1)

SS, stainless steel.
Common symbol, no significant difference between ligations; different symbol, significant difference between ligations.

Table 3 Mean frictional forces (standard deviation) for each module type and wire size combination.

Size	Order of ligation in terms of mean frictional (standard deviation) force (N) Smallest force → largest force				
0.017 × 0.025 inch	SS ligature[a] 0.43 (0.11)	Purple[ab] 0.53 (0.10)	Grey[bc] 0.59 (0.08)	SuperSlick[cd] 0.68 (0.11)	Alastik[d] 0.75 (0.12)
0.019 × 0.025 inch	SS ligature[a] 0.45 (0.14)	Alastik[ab] 0.50 (0.09)	Purple[ab] 0.56 (0.09)	Grey[c] 0.84 (0.15)	SuperSlick[c] 0.98 (0.13)

SS, stainless steel.
Common symbol, no significant difference between methods of ligation; different symbol, significant difference between methods of ligation.

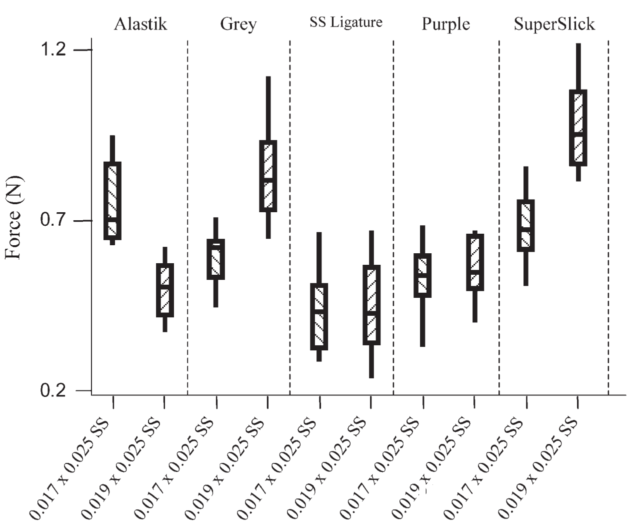

Figure 3 Boxplots for mean frictional force by method of ligation for 0.017 × 0.025 and 0.019 × 0.025 inch stainless steel wires.

modules. An interesting point to note for this wire type was the low mean frictional force when using the Alastik module (Figure 3).

Discussion

Previous investigations have focused on the effect of changes in wire type or wire dimension as a means of reducing friction (Kusy *et al.*, 1988; Kapila *et al.*, 1990; Keith *et al.*, 1994). The present study determined the effect of the force with which the archwire is seated into the bracket slot on frictional resistance. A validated testing system to eliminate binding between the wire and the bracket during the test phase was used (Khambay *et al.*, 2004). The sample size and crosshead speed, chosen for the determination of frictional resistance, were in accordance with those used in previous studies (Downing *et al.*, 1995; Taylor and Ison, 1996). In addition, the method of ligature placement allowed a standardized method of ligation for the SS ligatures, while the use of the ligature gun (Straight-shooter) allowed the elastomeric modules to be stretched by a standard amount prior to placement. Furthermore, all tests were carried out in the presence of whole, unstimulated saliva to replicate the clinical environment, in line with the recommendations of Kusy *et al.* (1991). The use of artificial saliva has been shown to be an inadequate substitute for human saliva in friction studies (Downing *et al.*, 1995).

When the mean tensile force of elastomeric modules was compared, it was noted that the grey and purple elastomeric modules displayed similar mean tensile force characteristics. This may be expected as the modules are identical except for colour. The SuperSlick and Alastik modules, however, have higher levels of mean tensile force and this may be due to the chemical composition or physical dimensions of the two module types. It would be logical to assume that the further a module is extended, the greater the tensile force and that the greater the mean tensile force, the greater the archwire seating force. The results of the present research show that with an extension of 5 mm the Alastik module produced a force of 1.7 ± 0.02 N. This result is not comparable with those of a previous investigation (Lam *et al.*, 2002), where modules were tested for tensile strength, i.e. to the point of failure. The values recorded in that study were as expected as the modules had been stretched beyond their elastic limit.

When the two archwire sizes were compared, for each of the five ligation methods, the median archwire seating force with the 0.019 × 0.025 inch wire was significantly greater than the median archwire seating force for the 0.017 × 0.025 inch wire. This shows that as the size of the archwire is increased, more of the bracket slot is filled with the wire leading to further displacement of the elastomeric module. The reaction force, which is the archwire seating force, will then seat the archwire more firmly into the bracket slot. The use of SS ligatures with seven turns produced the highest median archwire seating force. A possible explanation is that the SS ligature is not elastic and once the SS ligature seats the archwire into the bracket, further turns of the SS ligature will greatly increase the archwire seating force when compared with an elastomeric module. In general, the tensile force values indicated a similar order of force magnitude to the archwire seating forces. The grey module produced the least tensile and archwire seating force, while the opposite was true for the Alastik module.

There was no statistically significant difference between the ligation forces generated by the purple or grey modules used in combination with 0.019 × 0.025 inch SS wire. This was also the case for the tensile force tests. The mean frictional force produced by each module was, however, significantly different. The purple module produced the least force. This indicates that the surface characteristics of the module may be far more important than the physical characteristics, i.e. elasticity. Similarly, for the purple and SuperSlick modules, there were no statistically significant differences in the median archwire seating force, but the SuperSlick module was associated with a significantly higher mean frictional force.

The Alastik module also produced high median archwire seating forces but low mean frictional forces, when used in conjunction with a 0.019 × 0.025 inch SS wire. A possible explanation is that the bend in the module may prevent the entire module contacting the wire (Figure 4). Even though the Alastik module seats the wire firmly into the bracket slot, the incomplete contact between the module and the wire may allow easier sliding.

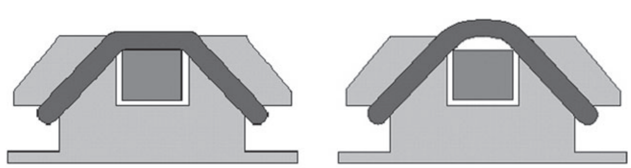

Figure 4 Diagrammatic representation of the possible interaction between a 0.019 × 0.025 inch stainless steel wire and bracket with (a) a conventional elastomeric module and (b) an Alastik module.

The use of SS ligatures produced the highest median archwire seating force, but the lowest mean friction force. This is in agreement with a previous study (Iwasaki *et al.*, 2003), which found that loose SS ligation was not associated with lower frictional forces than tight SS ligation. A possible explanation is that once the archwire begins to slide, the SS ligature may loosen slightly, unbind, and the friction will substantially reduce. Another possible explanation for a low friction force is that the wire, bracket and mode of ligation were all made of SS and thus all have the same coefficient of friction. The same study indicated that elastomeric modules generate 16.0 N of archwire seating force. Unfortunately, as the module manufacturer was not indicated in the study, direct comparisons with the findings of the present investigation cannot be made. However, an Alastik module would need about 5 mm of extension to produce this force (Lam *et al.*, 2002). Extension of this magnitude, however, is greater than that generated by placement of the module over a conventional wire/bracket arrangement. The value of 16.0 N, therefore, should be viewed with some caution as the module is not being extended enough to generate such a large force.

Conclusions

Statistically significant differences existed in the mean tensile forces and median archwire seating forces between the elastomeric modules. Grey modules with either size wire produced the lowest median archwire seating force, whereas SS ligatures produced the highest forces. SS ligatures with either wire produced the lowest mean frictional forces, whereas grey modules produced significantly higher mean frictional forces ($P < 0.01$). Some of the classic laws of friction do not appear to apply to orthodontic sliding of teeth along archwires. The surface characteristics of the modules may have a greater effect on friction than the seating force produced by the ligation method.

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