The effect upon friction of the degradation of orthodontic elastomeric modules

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SUMMARY Orthodontic elastomeric modules are susceptible to degradation and deformation after time in the mouth. The aims of this study were to determine whether degradation of elastomeric modules significantly affects friction during sliding mechanics and to investigate whether there is a difference in the behaviour of elastomeric modules after storage in both *in vivo* and *in vitro* environments. An Instron testing machine was used to determine the friction generated by elastomeric modules on 0.019 × 0.025 inch stainless steel archwires at 4 degrees of bracket tip. Four brands of modules were tested straight from the packet ($n = 15$), after storage in artificial saliva ($n = 15$), and after being in patients' mouths ($n = 32$). Modules were tested after 24 hours, 1 week, and 6 weeks after storage in both *in vivo* and *in vitro*. Analysis of variance revealed that the degradation of elastomeric modules had a variable affect upon friction and that each storage medium produced a distinct pattern of frictional resistance. Modules stored in artificial saliva experienced a significant reduction in friction ($P < 0.001$) while modules collected from patients' mouths produced similar friction to modules tested straight from the packet. TP Super Slick® modules under dry test conditions produced significantly greater friction than the other three types of test modules ($P < 0.001$). The structure and surface characteristics of elastomeric modules may affect frictional resistance when a bracket slides along an archwire. These effects vary according to time, storage medium, and brand of elastomeric material.

Introduction

The friction generated by any ligation method is an important variable in an orthodontic mechanism that uses sliding mechanics and friction must be borne in mind when deciding which ligation method to use. Friction is the resistance to motion when one object moves tangentially to another (Khambay *et al.*, 2005). The magnitude of friction depends partly on the amount of normal force pushing the two surfaces together and is therefore determined by the nature of ligation (Read-ward *et al.*, 1997; Hain *et al.*, 2003).

Frictional resistance is also determined by the coefficient of friction between the opposing materials (De Franco *et al.*, 1995). This may be dependent on the roughness, texture, or hardness of the contacting surfaces (Loftus *et al.*, 1999).

The classical laws of friction are accurate for metals under normal conditions. However, for other materials, extreme conditions, or biological systems, such as when brackets are slid along archwires, the laws are less reliable (O'Reilly *et al.*, 1999).

When clearance between an archwire and bracket slot exists, only 'classical friction' contributes to resistance to sliding. If contact occurs, binding additionally contributes to the resistance to sliding. As second-order angulations increases, a threshold is reached at which the critical angle

is significantly exceeded and consequently, binding plays a greater role in friction (Thorstenson and Kusy, 2003).

Elastomeric modules are made from polyurethane rubber and do not exhibit ideal elastic behaviour since their mechanical properties change with temperature and time (De Genova *et al.*, 1985; Chimenti *et al.*, 2005). The oral cavity is a highly complex and constantly changing environment and it is impossible to simulate such conditions accurately *in vitro*. The presence of complex oral flora and their by-products, as well as the accumulation of plaque, distinguishes any artificial experimental set-up from an actual *in vivo* situation (Eliades and Bourauel, 2005). Other factors may also alter the elastic properties of elastomeric ligatures, such as chemicals from saliva, food, or oral hygiene products. Thermal effects are due to the ingestion of hot and cold foods, and mechanical factors arise from mastication and oral hygiene techniques (Ash and Nikolai, 1978; Kuster *et al.*, 1986).

Addition of covalently bonded Metafasix lubricant to modules (Super Slick®; TP Orthodontics, LaPorte, Indiania, USA) is claimed to reduce friction by 60% compared with uncoated modules (Hain *et al.*, 2006). Griffiths *et al.* (2005), however, found that Super Slick® modules produced more friction than conventional modules except when they were used with ceramic brackets in wet conditions on 0.018 inch

round stainless steel wire. More recently, Crawford *et al.* (2010) investigated four different modules at six different time periods and found no difference in the frictional forces produced by Super Slick® modules compared with conventional modules. Unfortunately, this study was based on data from only five patients.

Orthodontic elastomeric modules are susceptible to degradation and deformation after a time in the mouth. The influence of these effects upon bracket friction has important clinical significance; yet, it has received relatively little attention. The aims of this study were

1. To determine whether degradation of elastomeric modules affects friction during sliding mechanics.
2. To establish if there is a difference in the behaviour of elastomeric modules after storage using *in vivo and in vitro* environments, respectively.

Materials and methods

A specially designed jig which permitted tip and torque to be varied between a bracket and archwire was used to record the frictional resistance between a straight length of 0.019×0.025 inch stainless steel archwire and a stainless steel upper premolar bracket ligated with a test elastomeric module.

Four degrees of tip and 0 degrees of torque were chosen for testing as it was felt that from previous studies, this would record an appropriate amount of measurable friction. Prior to testing, the jig was calibrated by testing 25 American Orthodontic modules for which there were data from previous studies using the same apparatus (Patel, 2005; Hamdan and Rock, 2008).

Testing was performed on an Instron machine (Model 5544; Instron Ltd, High Wycombe, Buckinghamshire, UK). Standard stainless steel upper premolar brackets (MBT™ prescription, Victory™ Twin series; 3M Unitek) were used. The wire span was set at 18.4 mm to represent the potential distance of the buccal segment between the distal edge of an upper canine bracket and the mesial end of the molar tube, using tooth sizes according to Ash (1993). Each time the archwire was changed, the wire length was standardized using a metal wedge measuring 18.4 mm in height. The free ends of the archwire were cinched down hard and the tension screw was calibrated to 300 g.

Mounted brackets were ligated to a 0.019×0.025 inch stainless steel archwire with test elastomeric ligatures. Each bracket was then pulled along the wire by means of a 0.9 mm hard steel wire loop attached to the crosshead of the Instron via a 100 N load cell. Each bracket was pulled 7 mm along the archwire at a crosshead speed of 10 mm/minute. The archwire was changed every 15 tests to prevent distortion and wear of the archwire. It was felt that using five carefully calibrated test brackets and removing bracket debris with compressed air every time the archwire was

changed would be sufficient to overcome bracket wear. Four brands of elastomeric modules were tested (Table 1).

The value of interest was the static friction as this is the friction which must be overcome to initiate tooth movement during orthodontic sliding. The maximum static frictional resistance was recorded for each test module and this was represented by the peak on the curve of the trace produced by the Instron.

In vitro storage and testing

Fifteen modules of each brand were each placed over upper premolar brackets attached to small lengths of 0.019×0.025 inch stainless steel archwire. For ease of module placement and removal, the brackets were pre-mounted onto brass rods. The modules were then stored in artificial saliva at 37°C for 24 hours, 1 week, and 6 weeks.

After the selected storage period, the modules were carefully removed from the brackets and placed in artificial saliva for 4 hours before testing. The modules were tested with this delay to reflect the *in vivo* part of the study as it was not possible to test the modules obtained from patients immediately. The frictional resistance of each test module was then measured as previously described. The storage conditions meant that the shape of the modules distorted, producing a groove delineating where the archwire had been and a dome where the module had been stretched over the bracket (Figure 1). During the testing, this shape was maintained on the test bracket.

Table 1 The four types of test modules.

Manufacturer	Colour	Code	Manufacturing process
American Orthodontics (AO)	Grey	854-262	Injection moulded
DB Orthodontics (DB)	White	DB03-0068	Injection moulded
Orthocare Elastaloops (OC)	White	466-435W	Injection moulded
TP Super Slick® (TP)	White	382-932	Injection moulded
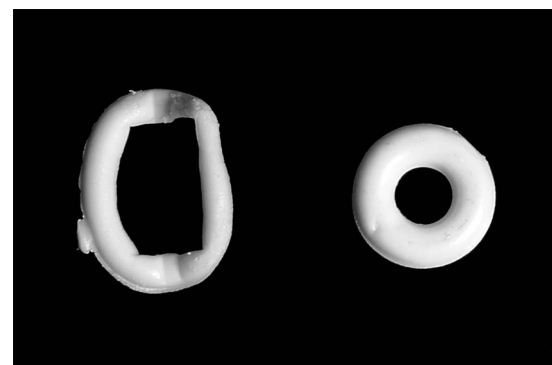
Figure 1 Distorted elastomeric module following storage.

Prior to module placement on the test jig, each module was gently blot dried with a paper towel and then further with endodontic paper points. At the beginning of each testing session, the apparatus set-up was calibrated by ensuring that the frictional resistance of a new grey American Orthodontics module was within 1 SD of the mean value obtained when these brackets were first measured.

Removing each module from a bracket in storage and then re-ligating it for testing may have altered the normal load as the elastomeric material relaxes with time. A pilot study was conducted to ensure that stress relaxation did not influence applied force. Five grey modules were removed fresh from the packet and the frictional resistance tested. The same modules were left *in situ* for 4 hours and re-tested. The frictional resistance for each of the same modules was found to be unchanged.

In vivo storage and testing

The sample size calculation was performed using data from Hain *et al.* (2006), which recorded that by soaking regular modules in saliva for 1 week, there was a significant reduction in friction from 2.00 (±0.39) to 1.54 (±0.30) N. Using Altman's (1991) Nomogram, it was estimated that 32 patients would be required to detect a similar difference at $P < 0.05$ with a power of 0.9. An extra three patients were recruited to allow for potential loss of subjects and test modules.

Of the 35 patients who were recruited to take part in the study, only 32 were included in the data analysis. Two patients dropped out of the study following recruitment and one patient missed an appointment at the 6 weeks time interval. In order to simplify the recruitment process of the clinical aspect of the trial, any patient with fully seating archwires (0.016 × 0.022 inch Nitinol and above) was recruited. The same test periods were used as for the laboratory-based storage conditions. Once test modules had been collected, they were stored in artificial saliva for up to 4 hours before testing. Each test module was tested in exactly the same way as for the laboratory-based storage conditions. Ethical approval was obtained from the West Midlands Research Ethics Committee (07/H1208/63) and informed consent was obtained from all patients taking part.

Descriptive statistics were used to evaluate the data for normality. One-way analysis of variance was used to detect and locate statistically significant differences. A paired *t*-test was used for further comparison where differences between pairs were considered to be significant within a test group. All statistical analyses were performed using Minitab® Release (Version 15, State College, Pennsylvania, USA).

Results

Before the study began, the jig was calibrated by testing a series of 25 American Orthodontics modules direct from the packet with 4 degrees of tip and 0 degrees of torque. The range of static force values was 3.5–5.12 N (SD 0.372 N). This was considered acceptable reliability.

Fifteen modules from four different manufacturers were tested for frictional resistance, straight from the packet, and after storage in artificial saliva at 37°C for 24 hours, 1 week, and 6 weeks (Table 2).

Mean friction for all four modules was greatest when the modules were fresh from the packet. After 24 hours storage in artificial saliva, friction reduced from 4.22 to 4.02 N and then further again to 3.63 after 1 week. After 6 weeks, friction increased to 3.89 N. Mean friction after 1 week was significantly less than the start value, $t = 4.75$, $P < 0.001$ (Figure 2).

Table 2 Mean, standard deviation, and range for all four modules unused and following storages in artificial saliva after 24 hours, 1 week, and 6 weeks. AO, American Orthodontics; DB, DB Orthodontics; OC, Orthocare Elastaloops; TP Super Slick®.

	N	Mean	Standard deviation	Minimum	Maximum
AO from packet	15	4.15	0.84	2.63	5.47
AO 24 h	15	3.81	0.521	3.08	4.64
AO 1 week	15	3.41	0.532	2.61	4.25
AO 6 weeks	15	3.88	0.799	2.75	5.41
DB from packet	15	3.86	0.922	2.4	5.43
DB 24 h	15	3.6	0.553	2.64	4.63
DB 1 week	15	3.36	0.435	2.65	3.94
DB 6 weeks	15	3.6	0.748	2.48	4.87
OC from packet	15	4.05	0.898	2.23	5.69
OC 24 h	15	3.93	0.793	2.64	5.03
OC 1 week	15	3.52	0.587	2.8	4.5
OC 6 weeks	15	3.54	0.527	2.74	4.67
TP from packet	15	4.84	0.831	3.19	6.03
TP 24 h	15	4.75	0.878	3.31	6.2
TP 1 week	15	4.23	0.662	2.86	5.05
TP 6 weeks	15	4.56	0.581	3.48	5.62
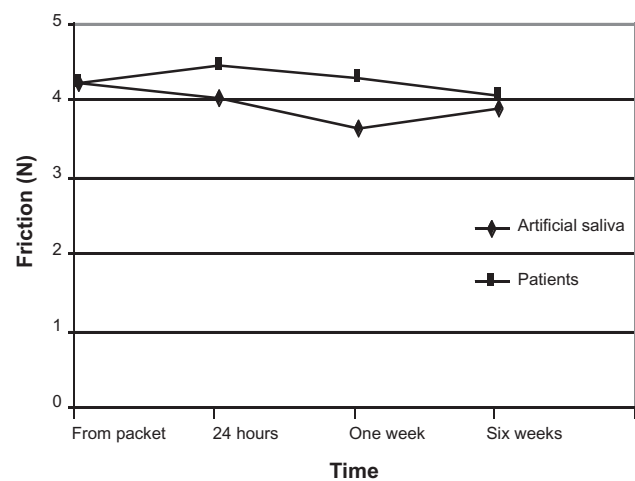
Figure 2 Comparison of friction generated by modules collected from artificaial saliva and patients' mouth.

The friction associated with modules collected from patients increased slightly but not significantly after 24 hours but then after 1 week reduced to a similar value to that of modules tested straight from the packet. After 6 weeks, friction reduced to 4.03 N, which was not significantly less than the friction straight from the packet (4.22 N). Mean friction after 24 hours was significantly greater that the mean friction after 6 weeks, $t = 4.55$, $P < 0.01$, but there was no significant difference between the 6 weeks and 'from packet' mean friction (Table 3, Figure 2).

Mean friction produced by TP Super Slick® modules was significantly greater than the three other brands of modules in all time periods in each of the storage mediums (Tables 2 and 3, Figure 3).

In comparing modules tested straight from the packet, stored in artificial saliva, and collected from patients regardless of time period and manufacturer, modules stored in artificial saliva produced significantly less friction, $P < 0.001$. Modules collected from patients produced virtually the same friction as modules tested straight from the packet (Table 4).

Discussion

The results of this study demonstrate that storage medium had a significant effect on the behaviour of the modules. Modules stored in artificial saliva experienced a significant reduction in friction, while modules collected from patients produced virtually the same friction as modules tested straight from the packet.

Previous studies investigating the force degradation of elastomerics demonstrate high initial force degradation (Wong, 1976; Rock *et al.*, 1986; Barreto, 2007) and this may explain the initial reduction of friction of modules stored in artificial saliva as seen in the first week of this study. Bortoly *et al.* (2008) stored modules in artificial

Table 3 Mean, standard deviation, and range for all four modules collected from patients' mouths after 24 hours, 1 week, and 6 weeks. AO, American Orthodontics; DB, DB Orthodontics; OC, Orthocare Elastaloops; TP Super Slick®.

	N	Mean	Standard deviation	Minimum	Maximum
AO 24 h	32	4.36	0.699	2.56	5.52
AO 1 week	32	4.15	0.738	2.35	5.54
AO 6 weeks	32	3.95	0.637	2.23	4.93
DB 24 h	32	4.15	0.881	2.62	6.06
DB 1 week	32	4.02	0.83	2.13	5.25
DB 6 weeks	32	4.00	0.641	2.46	5.34
OC 24 h	32	4.31	0.649	3.03	5.91
OC 1 week	32	4.13	0.915	2.23	5.71
OC 6 weeks	32	3.65	0.72	2.07	4.91
TP 24 h	32	4.92	0.709	3.55	7.37
TP 1 week	32	4.81	1.228	2.76	7.02
TP 6 weeks	32	4.50	0.799	3	6.11

saliva in a stretched state for 21 days. It was found that there was a parallel relationship between frictional and tensile forces produced by the test elastomeric modules, with reduction of both after 21 days. It was concluded that storage of elastomeric modules in a simulated oral environment renders their properties unstable, producing frictional forces that are more related to loss of tensile force than to the surface characteristics of the ligatures. In the present study, storage was extended to 6 weeks as this was felt to be more representative of the time period between orthodontic appointments. After 6 weeks storage in artificial saliva, the friction was less than that for unused modules but friction increased slightly for modules tested after 1 week to those tested at 6 weeks. Dowling *et al.* (1998) demonstrated that immersion of all types of elastomeric modules in a simulated oral environment resulted in a reduction in failure load strengths over time. However, when they related module immersion time with frictional resistance, they did not discover a discernible pattern. Some modules demonstrated increases in frictional levels; some maintained constant friction and others produced a decrease. They explained that factors other than the normal force applied by the ligature were involved in frictional resistance.

It is widely accepted that the conditions within the oral cavity markedly differ from controlled *in vitro* storage conditions. It was for this reason that it was decided to see if there was a difference between *in vitro* and *in vivo* storage conditions.
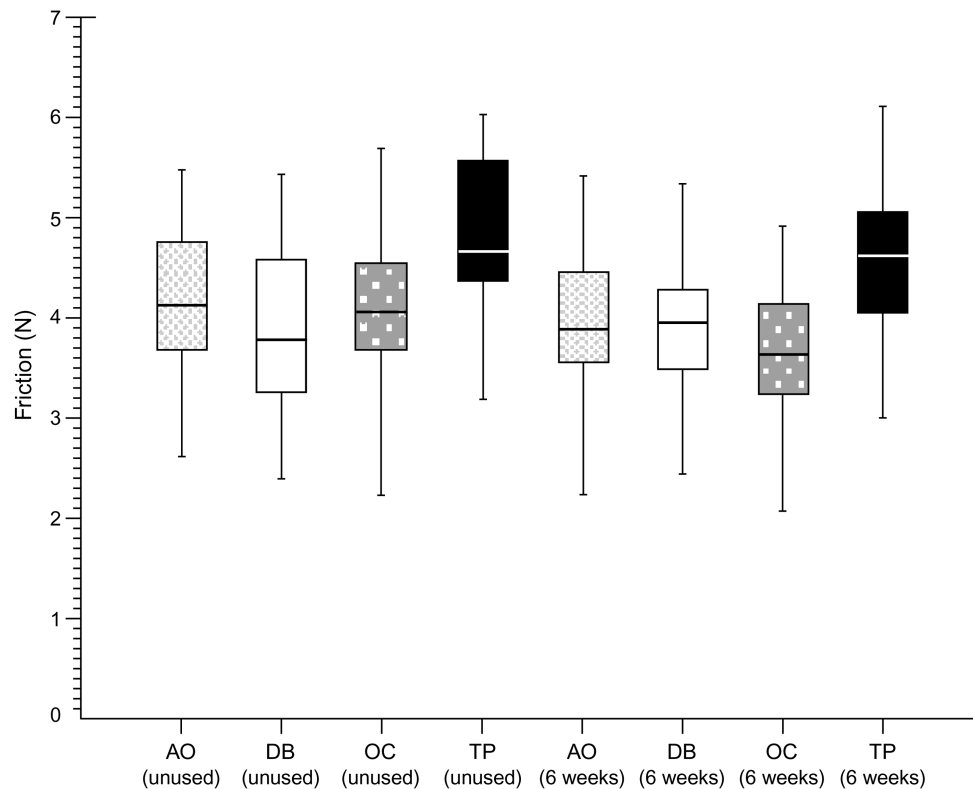
The friction produced by modules collected from patients varied in different ways from that of modules stored in artificial saliva. After 24 hours storage in the oral cavity, friction increased from 4.22 N fresh from the packet to 4.44 N and after 1 week, friction reduced to 4.27 N which was more a less the same value for modules tested straight from the packet. Dowling *et al.* (1998) found that four of seven groups showed increased frictional resistance when tested after 1 week. After 6 weeks, friction reduced to 4.03 N, which was not significantly less than the friction straight from the packet but was significantly less than the mean friction after 24 hours. There is a substantial amount of evidence to show that the normal force produced by elastomeric modules reduces with time (Wong, 1976; Rock *et al.*, 1986; Edwards *et al.*, 1995; Taloumis *et al.*, 1997; Dowling *et al.*, 1998; Barreto, 2007).The results of the present study agree with that of Dowling *et al.* (1998), in that factors other than force decay are responsible for the frictional resistance created by elastomeric modules. It is possible that these factors are acting at different stages in the life cycle of an elastomeric module and that the dynamics of the storage medium will affect the module at different time periods.

Although the tensile strength of modules reduces over time, frictional resistance may increase due to changes in the structure and surface characteristics of a module. Such

Figure 3 Boxplot showing the median, interquartile range, and minimum and maximum values generated by all four brands of module straight from the packet ($N = 15$) and after 6 weeks storage in artificial saliva and patients' mouths ($N = 47$).

Table 4 Friction for modules tested unused, stored in artificial saliva, and collected from patients' mouths regardless of time period and manufacturer.

Medium	N	Mean	Standard deviation
Unused	60	4.22	0.93
Artificial saliva	180	3.85	0.76
Patients' mouths	384	4.24	0.86

changes may negate the effect of force decay so that the true effect of this is masked, resulting in a number of scenarios:

1. Frictional resistance may increase because transformations in module structure and surface characteristics exceed the effect of module degradation.
2. Changes in structure and surface characteristics may balance the reduction in force decay to produce little or no change in frictional resistance.
3. Force decay of modules may be greater than the effect of changes in module structure and surface characteristics so that the resultant frictional resistance is less.
4. Changes in structure and surface characteristics may vary according to time and storage environment.

Taloumis *et al.* (1997) reported that, although they did not purposely examine any specific relationship with flash, they believed that flash left after manufacture may affect the consistency of force exerted by a ligature. Although the effect of flash was also not specifically investigated in this study and conclusions on its affect must be taken lightly, it was noted to be present on some of the modules tested in the present study (Figure 1). Flash on the inner and outer aspect of a module may contribute to structural changes that increase frictional resistance. It is possible for flash to become trapped between the archwire and bracket like a rug may be trapped in a closing door.

Polymeric coating

Super Slick® modules (TP) demonstrated significantly greater friction than the three other modules under all test conditions. This is in agreement with Griffiths *et al.* (2005) and Khambay *et al.* (2004) who demonstrated that Super Slick® modules offer no advantage over conventional round cross-sectional modules and if anything increase friction with 0.019 × 0.025 stainless steel archwires. When Super Slick® modules were applied to brackets, they did not stretch as easily as the other three modules. Consequently, the ligation force generated by Super Slick® modules may have been greater. Although TP modules produced the greatest friction, testing was done in a dry state. Perhaps, in the presence of saliva, the Metafasix lubricant may reduce friction as claimed by the manufacturer. However, conflicting evidence exists as to whether testing in a dry or

wet state influences frictional resistance. Testing in a wet state may reflect the actual clinical situation more accurately than dry testing but further clarification is required. Some studies suggest that saliva acts as an adhesive (Downing *et al.*, 1995), others promote the idea that saliva reduces friction (Baker *et al.*, 1987; Pratten *et al.*, 1990), whereas a third view is that saliva has a negligible effect on friction (Kusy *et al.*, 1991). It was decided that standardization would be best achieved if testing was conducted in the dry state as this was much easier to control.

Despite using a storage model to replicate *in vivo* conditions, it should be remembered that testing was performed *ex vivo*. Caution should be exercised extrapolating the findings of *ex vivo* studies to the clinical situation. A particular limitation of the study is the inability of the test jig to reproduce the complex mechanism of tooth movement that occurs with a fixed appliance in the mouth. It is difficult to recreate occlusal and muscular forces, tooth movement through bone, and the binding associated with bracket slots that are placed in different planes relative one another as one tooth tips or rotates while another uprights. The set-up of the test jig in this study contained only one test bracket ligated to an archwire. Testing designed to represent a buccal segment ought perhaps to incorporate multiple brackets, but this could have introduced further variables.

Four degrees of tip was chosen for testing since previous laboratory studies suggest that this would record an optimum amount of measurable friction and it was hoped that the testing would more accurately reflect the clinical situation (Hamdan and Rock, 2008). Loftus *et al.* (1999) recommend that if laboratory experiments aim to simulate orthodontic sliding, frictional forces should be tested in a model to incorporate the tip and rotation that occurs during clinical conditions. Clinically, during sliding mechanics, the applied force is not perfectly parallel in direction to the intended or actual sliding motion. As a result, teeth may tip and rotate in the direction of the applied force. It is thought that tooth movement occurs in a series of very small steps by which a tooth is guided along an archwire, experiencing tipping, binding, and finally uprighting movements. Each time the cycle begins static friction must be overcome in order to initiate tooth movement (Drescher *et al.*, 1989; Dowling *et al.*, 1998; Chimenti *et al.*, 2005).

Conclusions

The degradation of elastomeric modules has a variable affect upon friction during orthodontic sliding.

1. Modules stored in artificial saliva produced significantly less friction ($P < 0.001$) than modules tested straight from the packet.
2. Modules collected from patients' mouths produced similar friction to modules tested straight from the packet.

3. The results of the present study question the validity of using artificial saliva as a storage medium when testing elastomeric materials *in vitro*. Such is the diversity of the oral cavity that it is recommended to use patients' mouths as a storage medium for test materials in orthodontic research.
4. It may be advantageous to leave modules unchanged when low friction is desired. However, the amount of friction reduction is likely to be clinically insignificant and the side effect of loss of rotational control is of greater consequence. It is therefore advised that all modules should be changed at each routine appliance adjustment.
5. Under dry test conditions, TP Super Slick® modules produced significantly greater friction than the other three test modules ($P < 0.001$).

Funding

References

Altman D G 1991 Practical statistics for medical research. Chapman & Hill, London

Ash J L, Nikolai R J 1978 Relaxation of orthodontic elastomeric modules in vitro and in vivo. Journal of Dental Research 57: 685–690

Ash M J 1993 Wheeler's dental anatomy, physiology and occlusion. W. B. Saunders Co., Philadelphia

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

Barreto L S 2007 A laboratory investigation of the force delivery of elastomeric chains. Thesis, University of Birmingham

Bortoly T G, Guerrero A P, Rached R N, Tanaka O, Guariza-Filho O, Rosa A R 2008 Sliding resistance with esthetic ligatures: an in-vitro study. American Journal of Orthodontics and Dentofacial Orthopedics 133: 340

Chimenti C, Franchi L, Di Giuseppe M G, Lucci M 2005 Friction of orthodontic elastomeric ligatures with different dimensions. Angle Orthodontist 75: 421–425

Crawford N L, McCarthy C, Murphy T C, Benson P E 2010 Physical properties of conventional and Super Slick elastomeric ligatures after intraoral use. Angle Orthodontist 80: 175–181

De Franco D J, Spiller R E, von Fraunhofer J A 1995 Frictional resistance using Teflon-coated ligatures with various bracket-archwire combinations. Angle Orthodontist 65: 63–74

De Genova D C, McInnes-Ledoux P, Weinberg R, Shaye R 1985 Force degradation of orthodontic elastomeric chains—a product comparison study. American Journal of Orthodontics and Dentofacial Orthopedics 98: 404–410

Dowling P A, Jones W B, Lagerstrom L, Sandham J A 1998 An investigation into the behavioural characteristics of orthodontic elastomeric modules. British Journal of Orthodontics 25: 197–202

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: 141–146

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

Edwards G D, Davies E H, Jones S P 1995 The *ex vivo* effect of ligation technique on the static frictional resistance of stainless steel brackets and archwires. British Journal Orthodontics 22: 145–153

Eliades T, Bourauel C 2005 Intraoral aging of orthodontic materials: the picture we miss and its clinical relevance. American Journal of Orthodontics and Dentofacial Orthopedics 127: 403–412

Griffiths H S, Sherriff M, Ireland A J 2005 Resistance to sliding with 3 types of elastomeric modules. American Journal of Orthodontics and Dentofacial Orthopedics 127: 670–675

Hain M, Dhopatkar A, Rock P 2003 The effect of ligation method on friction in sliding mechanics. American Journal of Orthodontics Dentofacial and Orthopedics 123: 416–422

Hain M, Dhopatkar A, Rock P 2006 A comparison of different ligation methods on friction. American Journal of Orthodontics and Dentofacial Orthopedics 130: 666–670

Hamdan A, Rock P 2008 The effect of different combinations of tip and torque on archwire/bracket friction. European Journal of Orthodontics 30: 508–514

Khambay B, Millett D, McHugh S 2004 Evaluation of methods of archwire ligation on frictional resistance. European Journal of Orthodontics 26: 327–332

Khambay B, Millett D, McHugh S 2005 Archwire seating forces produced by different ligation methods and their effect on frictional resistance. European Journal of Orthodontics 27: 302–308

Kuster R, Ingervall B, Bürgin W 1986 Laboratory and intra-oral tests of the degradation of elastic chains. European Journal of Orthodontics 8: 202–208

Kusy R P, Whitley J Q, Prewitt M J 1991 Comparison of the frictional coefficients for selected archwire-bracket slot combinations in dry and wet states. Angle Orthodontist 61: 293–301

Loftus B P, Årtun J, Nicholls J I, Alonzo T A, Stoner J A 1999 Evaluation of friction during sliding tooth movement in various bracket-arch wire combinations. American Journal of Orthodontics and Dentofacial Orthopedics 116: 336–345

O'Reilly D, Dowling P A, Lagerstrom L, Swartz M L 1999 An ex vivo investigation into the effect of bracket displacement on the resistance to sliding. British Journal of Orthodontics 26: 219–227

Patel A M 2005 The effect of tip and torque combinations on friction between orthodontic brackets and archwires. Thesis, University of Birmingham

Pratten D H, Popli K, Germane N, Gunsolley J C 1990 Frictional resistance of ceramic and stainless steel orthodontic brackets. American Journal of Orthodontics and Dentofacial Orthopedics 98: 398–403

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

Rock W P, Wilson H J, Fisher S E 1986 Force reduction of orthodontic elastomeric chains after one month in the mouth. British Journal of Orthodontics 13: 147–150

Taloumis L J, Smith T M, Hondrum S O, Lorton L 1997 Force decay and deformation of orthodontic elastomers. American Journal of Orthodontics and Dentofacial Orthopedics 111: 1–11

Thorstenson G A, Kusy R P 2003 Effects of ligation type and method on the resistance to sliding of novel orthodontic brackets with second-order angulation in the dry and wet states. Angle Orthodontist 73: 418–430

Wong A K 1976 Orthodontic elastic materials. Angle Orthodontist 46: 196–205