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A comparative study of the static and kinetic frictional resistance of titanium molybdenum alloy archwires in stainless steel brackets

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SUMMARY This *ex vivo* study compared the static and kinetic frictional resistance of eight different archwires tested in a single, stainless steel, zero base 0.022 × 0.028 inch (0.56 × 0.711 mm) slot standard edgewise bracket. The archwires evaluated were 0.019 × 0.025 inch (0.483 × 0.636 mm) in dimension, manufactured from the following alloys: beta titanium (TMA™), 'low friction' coloured beta titanium (aqua, honeydew, purple and violet), ion-implanted beta titanium, Timolium™ and a stainless steel control. Prior to friction testing, bracket and archwire dimensions were measured by direct digital imaging via a desktop computer linked to a binocular light microscope. Frictional force was evaluated using an Instron universal testing machine. All experiments were carried out at room temperature, with no ligation, in the dry state with 20 degrees of added torque.

The results demonstrated that static and kinetic friction were statistically significant ($P < 0.001$) for all archwire types. Ion-implanted and standard TMA™ archwires were found to have no significant advantage over stainless steel. The archwire alloys may be ranked as follows: stainless steel produced the lowest frictional resistance followed by honeydew, ion-implanted TMA™ and Timolium™, with aqua, purple and violet producing frictional resistance values as high as standard TMA™. It was also found that the percentage difference between the archwire and bracket slot dimensions claimed by the manufacturers and those measured in this experiment produced tolerances ranging from +5.37 to –6.67 per cent.

Introduction

Literature review

Mitchell (2001) stated that the use of sliding mechanics in pre-adjusted orthodontic brackets is most applicable to move either individual teeth or blocks of teeth when using the pre-adjusted edgewise appliance technique. As the teeth are translated, forces develop which may inhibit their movement. If these forces are not considered and evaluated before treatment, and constantly re-evaluated during treatment, there may be anchorage loss and unfavourable tooth movement. Conversely, the clinician may encourage anchorage loss to achieve desirable tooth movements. A balance must be found depending upon the clinical situation.

The retarding force that develops when sliding mechanics are employed is a function of the dynamic relationship between archwires, brackets and ligation type in the oral environment. This force must be considered so that 'optimum biological forces' may be employed to produce the desired tooth movement without compromising the health and vitality of both the teeth and their supporting periodontal tissues.

Proffit (2000) reported that 50 per cent of the force necessary to initiate tooth movement is required to overcome the retarding force generated between brackets, archwires and ligatures. This implies that only 50 per cent of the force applied reaches the tooth and its supporting tissues. The absolute value for the optimum force required to produce 'biological tooth movement' is extremely difficult to quantify and it has been demonstrated that increasing the force increases the rate of orthodontic tooth movement up to a point (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980; Garner *et al.*, 1986; Tidy, 1989). Beyond this point, tooth movement fails to keep pace with increasing force application—there is an 'optimal range' for effective tooth movement. Ho and West (1991) found that the forces required to overcome friction *in vivo* are much less than those required *in vitro*. This illustrates that there are many different variables in action in the oral environment when a tooth moves under the influence of orthodontic forces.

Definition of terms

It is essential when examining the literature that the terms 'friction' and 'binding' are clearly defined. Although they both contribute to produce a force that resists sliding, they are entirely different entities and so should be considered as such.

Friction is defined as 'the resisting force tangential to the common boundaries between two or more bodies when, under the action of an external force, one body moves or tends to move relative to the surface of the other' (Kajdas *et al.*, 1990).

Binding may occur when point contacts are formed between bracket, archwires and/or ligatures producing a force couple that resists sliding. This force may prevent tooth movement and may also result in damage to the surface of the orthodontic appliance resulting in notching.

Tidy (1989) and O'Reilly *et al.* (1999) dispute whether the classic laws of friction alone apply when tooth movement occurs *in vivo*. It is postulated that the resistance to tooth movement in the clinical situation is a product of binding and releasing at the bracket, archwire and ligature interface. This stop–start motion occurs as the tooth is translated along the archwire in the classically described 'tip-upright, tip-upright' mechanism (Thurow, 1975; Drescher *et al.*, 1989; Tidy, 1989; Ireland *et al.*, 1991; Loftus *et al.*, 1999). However, as the surfaces of the slots and tubes of orthodontic fixtures and ligatures move over one another, it is also likely that true frictional forces will develop.

Although there is a large body of literature that illustrates the effect on retarding force when utilizing different orthodontic wire materials (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980; Garner *et al.*, 1986; Drescher *et al.*, 1989; Angolkar *et al.*, 1990; Kapila *et al.*, 1990; Vaughan *et al.*, 1995; Proffit, 2000) and bracket dimensions (Andreasen and Quevedo, 1970; Garner *et al.*, 1986; Tidy, 1989; Kapila *et al.*, 1990; Proffit, 2000) there is less work examining whether materials used by clinicians are of the dimensions stated by the manufacturers (Kusy and Whitley, 1990; Meling and Ødegaard, 1998; Siatkowski, 1999).

It is, therefore, probable that resistance to orthodontic tooth movement occurs as a result of the combined effects of the orthodontic materials utilized and as a result of friction, binding and notching in the oral environment. As yet, the individual contribution of each element to the resisting force remains undetermined.

Aims

The aim of this study was to measure the frictional forces generated *ex vivo* with the recently introduced beta titanium alloy archwires, both coloured and grey. These wires were compared with one another and with a stainless steel control. Bracket and archwire dimensions were also examined and their influence on the frictional forces considered. Beta titanium alloy archwires have been shown to develop frictional forces greater than stainless steel (Garner *et al.*, 1986; Drescher *et al.*, 1989; Kusy and Whitley, 1989, 1990; Tidy, 1989; Kapila *et al.*, 1990; Angolkar *et al.*, 1990; Vaughan *et al.*, 1995; Proffit, 2000). There have been recent technical developments in the manufacture of these beta titanium alloy archwires claimed to reduce their frictional characteristics.

Materials

Brackets

Forty Dyna-Lock standard edgewise twin (3M Unitek Dental Products, Monrovia, CA, USA), 0.022 × 0.028 inch (0.56 × 0.711 mm) slot maxillary central incisor brackets were used in testing. These twin brackets are milled from a solid blank of steel and have a zero degree tip and torque prescription. Five brackets were chosen from the same production batch for each wire group and were only used for one test.

Archwires

Five individual 6 cm lengths of archwire were cut from the supplied pre-formed archwire blanks and stored with their randomly assigned bracket. All archwires had 0.019 × 0.025 inch (0.483 × 0.636 mm) dimensions. The Timolium™ archwires were supplied by TP Orthodontics (LaPorte, IN, USA) and the remaining archwires by Ormco Corp. (Glendora, CA, USA).

Ligation, lubrication, temperature

The experiments were completed at a room temperature of 24°C in the dry state with no ligation. After archwire dimensions had been recorded, individual brackets were bonded with Araldite epoxy resin adhesive (Bostik Ltd, Leicester, UK) to individual base steel bars with dimensions of 150 × 20 × 3 mm. Each base steel bar had a line scribed in the midline, parallel to the long axis, to act as a guide for reproducible bond position and as a vertical when compared with the plumb line while testing.

Prior to bracket bonding, a 0.021 × 0.025 inch (0.533 × 0.636 mm) diameter archwire was secured into the slot with an elastomeric module. This archwire had been bent into a jig that passively enabled accurate paralleling of the bracket slot sides with the sides of the base steel bar, as described by Thomas *et al.* (1998) (Figure 1). A triangular metal wedge was prepared and secured to the base of each bracket mount at the time of examination to produce a torquing moment of 20 degrees when mounted in the jaws of the friction testing machine.

Method

Bracket and archwire measurement

Archwire and bracket slot dimensions were measured using a Meiji binocular light microscope (Meiji Labax Co., Tokyo, Japan) at a magnification of ×40. After operator calibration using a laser-etched grid of known

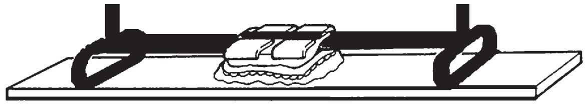

Figure 1 Line drawing to illustrate bracket positioning jig (redrawn from Thomas *et al.*, 1998).

dimension, measurements were taken manually from the screen of a computer by direct digital imaging using Global Lab Image software (Data Translation, Inc. and Acuity Imaging, Inc., Malborough, MA, USA). This system permits accurate measurement of objects under the microscope, transferring the images directly to a computer screen. From this image, the operator moves a cursor over the archwire/bracket slot and the dimensions are calculated by the computer program by evaluation of the screen pixels.

The archwire dimensions were recorded at random at three separate areas along the archwire and at five points within each area. These points were recorded between 1, 3 and 5 cm along the archwire for both the 0.019 and 0.025 inch (0.483 and 0.636 mm) dimensions of the rectangular archwires tested.

Friction testing

Each bracket and archwire was cleaned with methylated spirit and allowed to dry for at least 5 minutes prior to testing. The whole bracket mount assembly and triangular metal wedge was then fixed vertically in the jaws of the floor-mounted Instron 1193 Universal Testing Instrument (Instron Corp., MA, USA). A plumb line was hung to ensure that the bracket mount was parallel with the vertical line scribed on the steel bar base of the bracket mount assembly.

The 10 N load cell was calibrated between 0 and 10 N and the archwire was drawn through the bracket as the crosshead moved inferiorly at a rate of 0.5 mm/minute. This crosshead speed was selected as Ireland *et al.* (1991) found no significant difference when using crosshead speeds from 0.5 to 50 mm/minute. The resulting frictional force was recorded by a pen stylus on a moving graph paper chart travelling at a rate of 10 mm/minute. Each bracket and archwire combination was tested over a 2 minute period and each test was repeated five times with new brackets and archwires for each test; 80 tests were performed in total.

Digitization of friction tracings

The individual friction tracings were scanned and imported into Microsoft PhotoDraw (Microsoft Corp., Redmond, WA, USA). The images were cropped and filled with contrast and imported into the mathematics software package Mathcad Professional (Mathsoft, Cambridge, MA, USA). A computer program especially written and adapted for this study was then used to calculate the area under the curve of the graphs. This was calibrated and tested on three images of known dimensions prior to scanning the friction tracings. This produced a mean error of 0.125 per cent and the program was deemed sufficiently accurate to calculate the area under the graphs. The methodology is illustrated in Figure 2.

Results

The results were examined using one-way analysis of variance (ANOVA) with the data entered into the Sigmastat statistical package (Microsoft). Initial data analysis was used to determine the mean and standard error of the mean (Table 1).

Alloy type and static and kinetic friction

Both mean static and mean kinetic friction were found to be statistically significant at the $P < 0.001$ level for

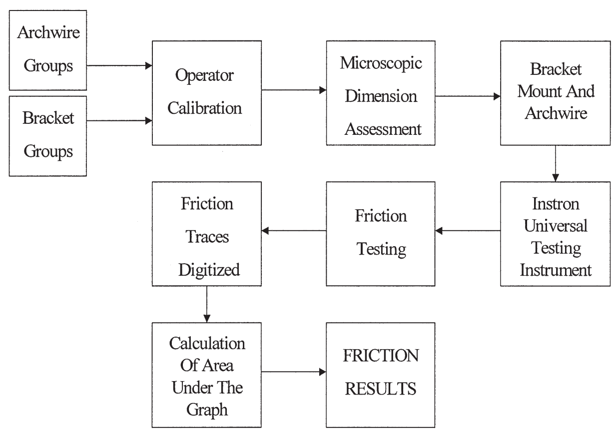

Figure 2 Flow diagram to illustrate the key points in the methodology.

Table 1 Static and kinetic friction values for archwire alloys.

Material	Static friction	Kinetic friction
Aqua TMA™	6.48 ± 0.14	6.08 ± 0.19
Honeydew TMA™	3.00 ± 0.11	3.00 ± 0.03
Purple TMA™	6.26 ± 0.18	5.70 ± 0.07
Violet TMA™	5.94 ± 0.20	5.62 ± 0.13
TMA™	6.16 ± 0.16	5.50 ± 0.32
Ion-implanted TMA™	3.14 ± 0.08	3.00 ± 0.11
Stainless steel	1.80 ± 0.13	1.72 ± 0.08
Timolium™	4.64 ± 0.18	5.02 ± 0.12

All units are in Newton seconds as determined by the area under the curve.
Results = mean ± standard error of the mean.

all archwire types (Table 1 and Figure 3) when analysed by the pairwise multiple comparison procedure, the Student–Keuls–Newman (SKN) method. Correlations were found to exist between the archwire groups and the results for static and kinetic friction. This is illustrated by the linear regression curve in Figure 4.

Archwire dimension

The archwire dimensions recorded in this study were compared with those stated by the manufacturers using the pairwise multiple comparison procedure (SKN method). For the 0.019 inch (0.483 mm) dimension, this illustrated that the aqua, honeydew, purple, violet TMA™ and Timolium™ were of similar dimensions. The remaining three alloys were different from one another and also from the main group of five.

For the 0.025 inch (0.636 mm) dimension, the same five wire groups as above were of similar dimensions, the TMA™ and ion-implanted TMA™ were similar, but the stainless steel wires were of statistically different dimensions from the other two groups of archwires.

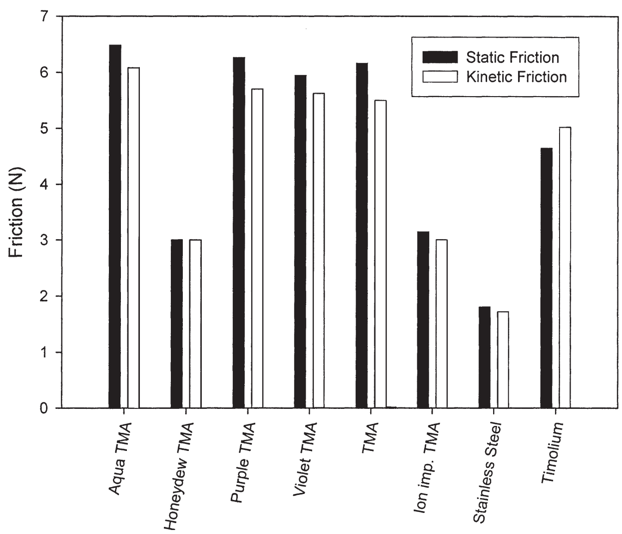

Figure 3 Histogram illustrating the relationship between static friction, kinetic friction and archwire alloy.

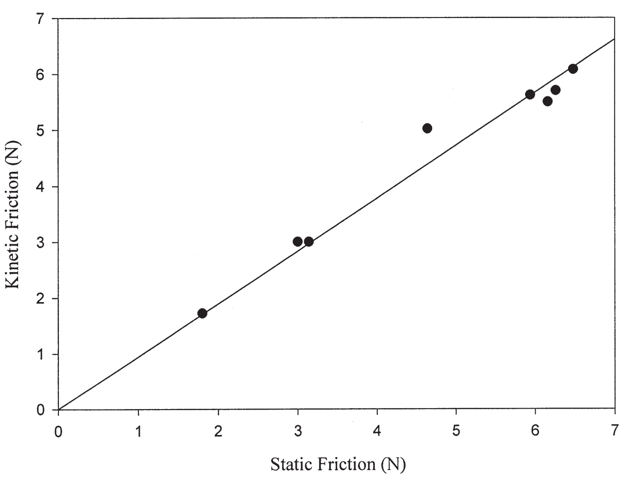

Figure 4 Linear regression curve showing the relationship between kinetic and static friction.

Archwire dimension and kinetic friction

Wire dimensions were related to kinetic friction by linear regression curves (data not shown). Static friction was not tested as there was no statistically significant difference between it and kinetic friction (Figure 4). There was little correlation between percentage archwire dimension and bracket slot width when compared with kinetic friction (data not shown). The effect of a non-uniform bracket slot width and archwire dimensions on frictional force was nullified in this experiment. This may be due to the fact that the experimentally placed torque results in archwire and bracket contact due to decreased torsional clearance as the 'slop' in the bracket is taken up.

Bracket slot dimension

Bracket slot width was examined from the slot dimension data. With the SKN method, power in this study was not of a sufficient magnitude to show that the bracket slot width caused the differing frictional forces seen between the archwire groups.

Manufacturers' stated bracket and archwire dimensions

When comparing the manufacturers' stated dimensions for both brackets and archwires as percentages, there were some interesting trends. Archwire width (0.019 inch/0.483 mm) was, on average, 2.99 per cent smaller than stated, archwire height (0.025 inch/0.636 mm) was 6.67 per cent smaller than stated and bracket slot width (0.022 inch/0.56 mm) was 5.37 per cent larger than stated (Table 2).

Discussion

When closing space or reducing moderate overjets using sliding mechanics in clinical orthodontic practice, the significance of frictional force may not always be apparent. However, in those cases where anchorage balance is marginal, or where sliding mechanics fail, frictional forces may result in loss of anchorage. Unfavourable tooth movement may result unless there is practical intervention and poor occlusal and aesthetic results may occur.

This laboratory-based *ex vivo* study was designed to compare the frictional forces that develop when sliding

Table 2 Percentage of measured dimensions compared with those given by the manufacturers.

Archwire alloy type	Archwire		Bracket
	Wire dimension 0.019 inch (0.483 cm)	Wire dimension 0.025 inch (0.636 cm)	Slot width 0.022 inch (0.560 cm)
Aqua TMA™	100.79	97.64	104.43
Honeydew TMA™	102.69	98.99	103.68
Purple TMA™	99.88	97.67	105.61
Violet TMA™	101.24	98.68	105.03
TMA™	93.79	88.21	107.36
Ion-implanted TMA™	90.81	85.79	105.64
Stainless steel	84.76	81.13	105.07
Timolium™	100.83	98.49	106.11
Mean percentage	97.01	93.33	105.37

titanium molybdenum alloy archwires through stainless steel brackets. Archwires constructed from these alloys have been shown to perform poorly when using sliding mechanics when compared with stainless steel archwires (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980; Garner *et al.*, 1986; Drescher *et al.*, 1989; Angolkar *et al.*, 1990; Kapila *et al.*, 1990; Vaughan *et al.*, 1995; Proffit, 2000). The balance of this evidence suggests that this is likely to be as a result of the physical and surface characteristics of archwires constructed from this alloy.

Manufacturers have, therefore, attempted to reduce the deleterious effects of the frictional characteristics of these wires. By passing a direct electrical current through titanium alloys immersed as the anode in an electrolyte, manufacturers are able to colour orthodontic archwires and they claim these coloured TMA™ archwires have improved surface finish. The different colours are obtained by varying the voltage applied as this affects the thickness and, hence, the light refractive properties of the titanium oxide layer.

Ion implantation is achieved in a vacuum chamber by accelerating a vapour flux of ions against a target archwire via an electron beam evaporator. Burstone and Farzin-Nia (1995) have shown that this technique brings the possibility of increasing archwire hardness, reducing flexibility and again improving surface finish as ions penetrate the surface. However, to achieve the best possible reduction in frictional force when using these ion-implanted materials, both the bracket and the archwire should be treated and repeatedly so.

This study was designed to evaluate whether these claims are valid. There are, however, many difficulties in attempting to relate the findings of an *ex vivo* study to the clinical situation. The laboratory-based findings regarding the interaction of two surfaces of differing material and configuration must bear some significance. There are many potential sources of error that invade the protocol of an investigation such as this, but all efforts, as follows, were made to reduce the influence of these on the findings of this study.

Brackets

A non-pre-adjusted system was chosen so that torque added experimentally was the only torque to affect the frictional forces recorded. Studies adding torque to pre-adjusted bracket systems bonded with their bases fully in contact with their bracket mount, simply evaluate the combined effects of the torque in the bracket and the experimentally added torque.

Ligation

Ligation was not used in this study. When evaluating frictional forces reported in studies that have used ligation, it is not possible to determine whether the frictional forces recorded are a result of the true interaction of the different materials tested, or a combination of this and the forces produced by ligation.

Bracket and archwire measurement

The data currently available state that archwires of small dimensions produce reduced frictional forces compared with larger dimension archwires (Andreasen and Quevedo, 1970; Garner *et al.*, 1986; Drescher *et al.*, 1989; Angolkar *et al.*, 1990; Kapila *et al.*, 1990; Vaughan *et al.*, 1995). Although wires and brackets of known dimension were supplied, these values were scrutinized to evaluate whether or not their size had any significant effect on the frictional forces noted.

Bracket positioning

The jig used in this study (Figure 1) has been described in the literature by Thomas *et al.* (1998) and was constructed from a wire with dimensions of 0.021×0.025 inches (0.533×0.636 mm). This dimension of wire has 3.8 degrees of slop when used in a bracket slot of dimension 0.022×0.028 inch (0.56×0.711 mm). The jig was designed to place the bracket in a reproducible position where the effect of angulation is minimized during bonding to the base steel bar.

Friction traces and data recording

There was considerable variation in magnitude, amplitude and waveform of the friction traces recorded for all tests. The recording of static friction is simple, as a clear and easily measurable maximum is produced on the graph paper. The variation in the peaks and troughs during kinetic friction produces interpretation difficulties in that if one was to take recordings over finite time periods or at predetermined points in time, considerable error may be incorporated into the data as peaks and troughs are repeatedly over- or under-recorded.

Matthews *et al.* (1990) reported that questions raised by a study that produces graphical curves are likely to be answered by the calculation of the area under the curve, producing results that are more likely to be statistically valid. The friction tracings from this study were digitized calculating the area under the curve over a known time period and from this kinetic friction values were computed.

Results compared with previous reports

The results noted from the present experiment are similar to those in the orthodontic literature (Drescher *et al.*, 1989; Tidy, 1989; Burstone and Farzin-Nia, 1995). Burstone and Farzin-Nia (1995) reported that when comparing honeydew TMA™ with stainless steel, similar static and kinetic frictional force traces were generated. Those researchers, however, found lower frictional forces when testing the coloured and ion-implanted TMA™ wires when compared with untreated TMA™. In that study, however, sliding of the archwires was against flat pieces of stainless steel with loads applied, rather than sliding in brackets.

Frictional forces of 5 N for TMA™ and 2 N for stainless steel when sliding in steel brackets have also been reported by Drescher *et al.* (1989) and Tidy (1989). The former researchers also related increased friction to increased archwire flexibility and stated that force must increase six-fold when using TMA™ archwires for sliding mechanics. It is likely that this amount of force may exceed that of standard anchorage units and may also produce archform changes when sliding on a flexible archwire.

Manufacturers' stated dimensions

Meling and Ødegaard (1998), Kusy and Whitley (1990) and Siatkowski (1999) found that both archwires and brackets may be smaller or exceed the manufacturers' stated dimensions. Indeed, the cross-section of the rectangular wires examined in this study had significant edge bevel so reducing the dimension of the wires and their effectiveness, especially when torque is required. This has been reported by Siatkowski (1999) to cause the loss of incisal edge position by an average of 2.03 mm for maxillary incisors and 1.8 mm for mandibular incisors as a result of incomplete torque expression.

Static and kinetic friction

As stated earlier, pure static friction is greater than pure kinetic friction. That would seem not to be the case in clinical orthodontics. When faced with a situation in which the teeth fail to slide, the clinician should be aware of methods that may be utilized to overcome this, including the use of closing looped TMA™ archwires which may be bent up to permit 'friction-free' orthodontic space closure.

Conclusions

This *ex vivo* study has illustrated that:

1. Archwires constructed from stainless steel produce the lowest coefficients of static and kinetic friction during sliding mechanics.
2. Honeydew and ion-implanted TMA™ may allow space closure with the development of only minimal frictional forces.
3. Aqua, purple and violet produce frictional force values as high as standard TMA™. Timolium™ results in frictional forces between those seen in the aqua, purple and violet group and the honeydew and ion-implanted TMA™ archwire group.
4. The dimensions of materials such as archwires and brackets may not be the same as those stated by the manufacturers. This has implications regarding final tooth position as bracket and archwire combinations may not express full bracket prescription. This may result in under-correction of the inclination and angulation of individual or groups of teeth.

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