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Dynamic frictional behaviour of orthodontic archwires and brackets

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SUMMARY The aim of this study was to evaluate the frictional behaviour of 15 different archwires and 16 different brackets using small oscillating displacements when opposed to a standard stainless steel bracket or a standard stainless steel wire. Tests were run according to a pilot study at a frequency of 1 Hz and with a reciprocating tangential displacement of 200 μm, while the wire remained centred in the bracket slot under a load of 2 N.

The results indicated a significant difference between the evaluated wires and brackets. The mean coefficient of friction (COF) of the wires varied from 0.16 for Imagination NiTi tooth-coloured wire to 0.69 for the True Chrome Resilient Purple wire, while for the brackets it ranged from 0.39 for Ultratrimm to 0.72 for the Master Series. The fact that in this study, a large number of different commercially available archwires and brackets were evaluated with the same apparatus according to the same protocol, allows a direct comparison of the different archwire and bracket combinations, and can assist in the choice of the optimal bracket–wire combination with regard to friction.

Introduction

Moving teeth or closing extraction sites with fixed appliances creates a relative motion at contacting surfaces between brackets and archwires. Friction is the resistance to motion that exists when a solid is moved tangentially with respect to the surface of another contacting solid (Rabinowicz, 1965). Friction is, thus, inherent to sliding systems and influences, e.g. in orthodontics the rate of tooth movement (Taylor and Ison, 1996). Friction force, F_F, counteracts the intended movement of contacting surfaces, and is directly related to normal force, F_N. F_N acts perpendicular to the sliding direction and is applied in the case of archwires through the use of elastic modules or metal ligatures to tie them into the bracket slot. The coefficient of friction, μ, is a dimensionless parameter defined as the ratio between F_F and F_N.

For a better understanding of friction it is important to know the role of key factors in the origin of friction. Many studies have been conducted on orthodontic archwires and brackets and the following factors influencing friction have been identified: ligation type, force applied, bracket–wire clearance, wire size and morphology, bracket dimensions, torque at the bracket–wire interface, type of motion at the bracket–wire interface, and, of course, the type of bracket and wire materials used (Tselepis *et al.*, 1994; Braun *et al.*, 1999).

Each orthodontic material used in a bracket–wire combination (e.g. stainless steel) gives rise to a specific coefficient of friction (COF). The latter is dependent on the surface conditions and the material characteristics of the contacting materials. It is important to note that the COF is independent of the apparent area of contact. Thus, large and small objects of the same material have an identical COF, well known in material engineering, even for materials commonly used in orthodontics. The mechanical and physical properties of these materials are listed in specific material engineering handbooks (Budinski, 1992). A significant difference is frequently noticed between the COF reported for materials, such as stainless steel (Keith *et al.*, 1993; Kusy and Whitley, 1997) and those published in material engineering handbooks. This discrepancy may be due to differences in test set-up or in the surface conditions of the samples tested (oxidized, degreased, oiled, dry, wet, roughness, etc.).

In addition, the F_F required to start sliding (static friction) is usually greater than the force required to maintain sliding (dynamic friction). As a consequence, a differentiation has to be made between the static and kinetic aspects of friction (Rabinowicz, 1965; Braun *et al.*, 1999). Most F_F studies have been conducted under steady-state conditions using a linear unidirectional sliding test set-up (Drescher *et al.*, 1989; Kusy *et al.*, 1992; Kuroe *et al.*, 1994; Tselepis *et al.*, 1994; Vaughan *et al.*, 1995; Yamaguchi *et al.*, 1996). However, the oral environment is dynamic and studies on the frictional resistance of archwires should simulate the dynamics of the oral cavity (Braun *et al.*, 1999). Recently, a fretting machine available at the Department of Metallurgy and Materials Engineering (MTM), Katholieke Universiteit Leuven, Leuven, Belgium (Mohrbacher *et al.*, 1995) was adapted for evaluating the frictional behaviour of orthodontic materials such as brackets and archwires. Small reciprocating tangential displacements allow online recording of F_F and, thus, calculation of the dynamic frictional properties of any oscillating bracket–wire combination (Willems *et al.*, 2001).

The aim of this study was to evaluate the frictional behaviour of a number of commercially available archwires and brackets compared with a standard stainless steel bracket or a standard stainless steel wire. This was undertaken dynamically using the MTM fretting machine operated in an ambient air temperature of 23°C and 50 per cent relative humidity.

Materials and methods

The frictional behaviour of 15 commercially available archwires and 16 brackets was evaluated in the MTM fretting dynamic test set-up. All archwires were compared with a standard stainless steel orthodontic bracket, namely Miniature Twin with a 0.018 inch slot (3M Unitek, Monrovia, California, USA). Archwires with two different cross-sections were investigated, namely 0.017 × 0.025 and 0.016 × 0.022 inch rectangular wires (Table 1). All orthodontic brackets were compared with a standard stainless steel archwire with a cross-section of 0.017 × 0.025 inches (3M Unitek) (Table 2).

The MTM fretting machine was calibrated according to the method reported previously (Willems *et al.*, 2001). The reference bracket was mounted on a stainless steel sphere of 10 mm diameter. The stainless steel spheres were grid blasted to increase their surface roughness and to improve adhesion between the bracket and sphere. Subsequently, the sphere was coated with a layer of silane using a Silicoater system (Silicoup Sililink, Heraeus Külzer, Wehrheim, Germany) according to the manufacturer's instructions. The orthodontic bracket adhesive Concise (3M Unitek) was used for all bonding procedures. This chemical-cure adhesive was chosen for its good performance (Willems *et al.*, 1997). The reference bracket bonded to the metallic sphere was mounted on the *Z*-axis of the MTM fretting apparatus and the reference bracket was positioned using a 0.018 × 0.025 inch wire mounted on the wire sample holder. The reference brackets were locked in that position.

Before running the fretting test, the positioning wire was replaced by a section (20 mm) of one of the wires to be evaluated (Table 1). For exchanging the wires, the reference bracket mounted to the *Z*-axis was electronically moved upwards a few millimetres, enabling the operator to change the positioning wire and to mount the next test wire. In this way, the position of the wire sample holder was not changed with respect to the bracket. However, engaging a test wire with a smaller wire size resulted in extra clearance between the bracket and wire. This clearance was symmetrically distributed in the bracket slot by electronically moving the axis containing the reference bracket over half the distance of the clearance. This procedure is described as the centred positioning method (Willems *et al.*, 2001).

To remove any grease or other lubricant, the wire and bracket were cleaned with 90 per cent ethanol and dried with mild warm air before mounting in the test rig.

To evaluate the orthodontic brackets, the same centred positioning method was used while the positioning wire was replaced by the reference wire.

Finally, a load of 2 N was applied through the *Z*-axis of the MTM fretting apparatus, positioning the bracket over the wire with a strain, simulating that of an elastic module. With the MTM fretting machine, an oscillating lateral displacement of 200 μm was applied to the contacting surfaces at a frequency of 1 Hz in ambient air of 23°C and a relative humidity of 50 per cent. Initial tests were undertaken with this new device under 'dry' conditions in order to obtain reproducible results that could serve as a reference for comparison with existing

Table 1 The 15 evaluated archwires.

Product	Dimensions (inches)	Manufacturer
Imagination NiTi (tooth coloured)	0.016 × 0.022	Gestenco, Göteborg, Sweden
Neo Sentalloy	0.016 × 0.022	GAC, Central Islip, New York, USA
Bioforce Sentalloy	0.016 × 0.022	GAC
Titanium Memory Heat Activated	0.017 × 0.025	American Orthodontics, Sheboygan, Wisconsin, USA
Twist Wire Arches	0.017 × 0.025	American Orthodontics
Standard Edgewise	0.017 × 0.025	American Orthodontics
Goldtone Edgewise	0.017 × 0.025	American Orthodontics
Natural Arch 8 Strand Woven	0.017 × 0.025	American Orthodontics
Nubryte	0.017 × 0.025	GAC
Titanium Memory Force 1 Cat	0.017 × 0.025	GAC
Flex VIII Braided Preformed Arch Blanks	0.017 × 0.025	Rocky Mountain Orthodontics, Denver, Colorado, USA
True Chrome Resilient Purple	0.017 × 0.025	Rocky Mountain Orthodontics
Elgiloy Blue (soft)	0.017 × 0.025	Rocky Mountain Orthodontics
Elgiloy Yellow (ductile)	0.017 × 0.025	Rocky Mountain Orthodontics
Stainless Steel Rectangular	0.017 × 0.025	3M Unitek, Monrovia, California, USA

Table 2 The 16 evaluated brackets.

Product	Material	Dimensions (inches)	Manufacturer
Fascination	Ceramic	0.018 × 0.030	Dentaurum, Pforzheim, Germany
Vogue MLB Standard Edgewise	PB CR*	0.018 × 0.025	GAC, Central Islip, New York, USA
Allure Edgewise	Ceramic	0.018 × 0.025	GAC
Elan TEW	PB CH SS**	0.018 × 0.025	GAC
Master Series Master Series	Metal	0.018 × 0.025	American Orthodontics, Sheboygan, Wisconsin, USA
Master Series Friction Free	Metal	0.018 × 0.025	American Orthodontics
Master Series Mini Master	Metal	0.018 × 0.025	American Orthodontics
Master Series IBD	Metal	0.018 × 0.025	American Orthodontics
Ultratrimm	Metal	0.018 × 0.030	Dentaurum
Discovery	Metal	0.018 × 0.030	Dentaurum
TEW	Metal	0.018 × 0.025	GAC
Standard Edgewise	Metal	0.018 × 0.025	GAC
Minach	Metal	0.018 × 0.025	GAC
Mini-Taurus	Metal	0.018 × 0.025	Rocky Mountain Orthodontics, Denver, Colorado, USA
Synergy	Metal	0.018 × 0.025	Rocky Mountain Orthodontics
Miniature Twin	Metal	0.018 × 0.025	3M Unitek, Monrovia, California, USA

*PB, plastic bracket; CR, ceramic reinforcement.
**PB, plastic bracket (low absorbent polycarbonate); CH, ceramic for hardness; SS, stainless steel insert.

data. Each test consisted of 20 cycles of back and forth movements, with 10 tests being run for each type of wire. For each separate test run, a new piece of wire and a new reference bracket were mounted. These specific parameters and data processing procedures were chosen based on the results of an earlier calibration study (Willems *et al.*, 2001).

Statistical analysis was performed using the general linear models procedure of the SAS statistical package (SAS Institute, Cary, North Carolina, USA) with a Tukey's studentized range test for the variable being COF. ANOVA enabled a comparison of all brackets. The minimum level of significance was set at 0.05.

Results

The means and standard deviations of the *in vitro* COF for the different materials tested are shown in Figures 1 and 2 and listed in Tables 3 and 4. The mean COF of the evaluated archwires varied from 0.16 for Imagination NiTi tooth-coloured wire to 0.69 for True Chrome Resilient Purple wire, while for the evaluated brackets the COF ranged from 0.39 for Ultratrimm to 0.72 for the Master Series. The stainless steel reference wire and bracket generated a mean COF of 0.49, which was comparable with the results reported in an earlier study (Willems *et al.*, 2001). This confirms that the MTM fretting apparatus provides reproducible results. Other stainless steel wires and brackets included also showed comparable findings. ANOVA showed a general significant difference. The results of Tukey's studentized range test demonstrated significant differences in the COF for the evaluated wires and these are summarized in Figures 1 and 2.

Discussion

In this study, 15 commercially available archwires and 16 commercially available brackets were evaluated with the same apparatus according to the same protocol, which allowed a perfect comparison of the different archwire and bracket combinations. Friction studies frequently only report the evaluation of one or a few materials tested, whether these are newly developed or existing products (Drescher *et al.*, 1989; Kuroe *et al.*, 1994; Tselepis *et al.*, 1994; Vaughan *et al.*, 1995; Yamaguchi *et al.*, 1996). In addition, most authors use different protocols or even have different approaches to evaluate the friction generated in these bracket–wire combinations. Thus, the published results of many studies are difficult to compare.

The MTM fretting apparatus has proven to deliver reproducible measurements, not only in a calibration study (Willems *et al.*, 2001) but also in the present investigation. This was demonstrated by including the 0.017 × 0.025 inch reference stainless steel rectangular wire. The obtained COF of 0.49 showed no significant difference with previously obtained values (Willems *et al.*, 2001). Similar results were found for the reference bracket.

Related to the evaluation of friction, it has been argued that tying the wire into the bracket slot by using elastics or metal ligatures is arbitrary (Rock and Wilson, 1989; Bednar *et al.*, 1991). Indeed, it is often difficult to objectively measure the tying force and to keep that force constant throughout the complete evaluation. However, in the MTM fretting machine, a vertical load of 2 N is applied to the bracket–wire combination, thus simulating a constant tying force. This normal load was kept constant during testing and was applied after the

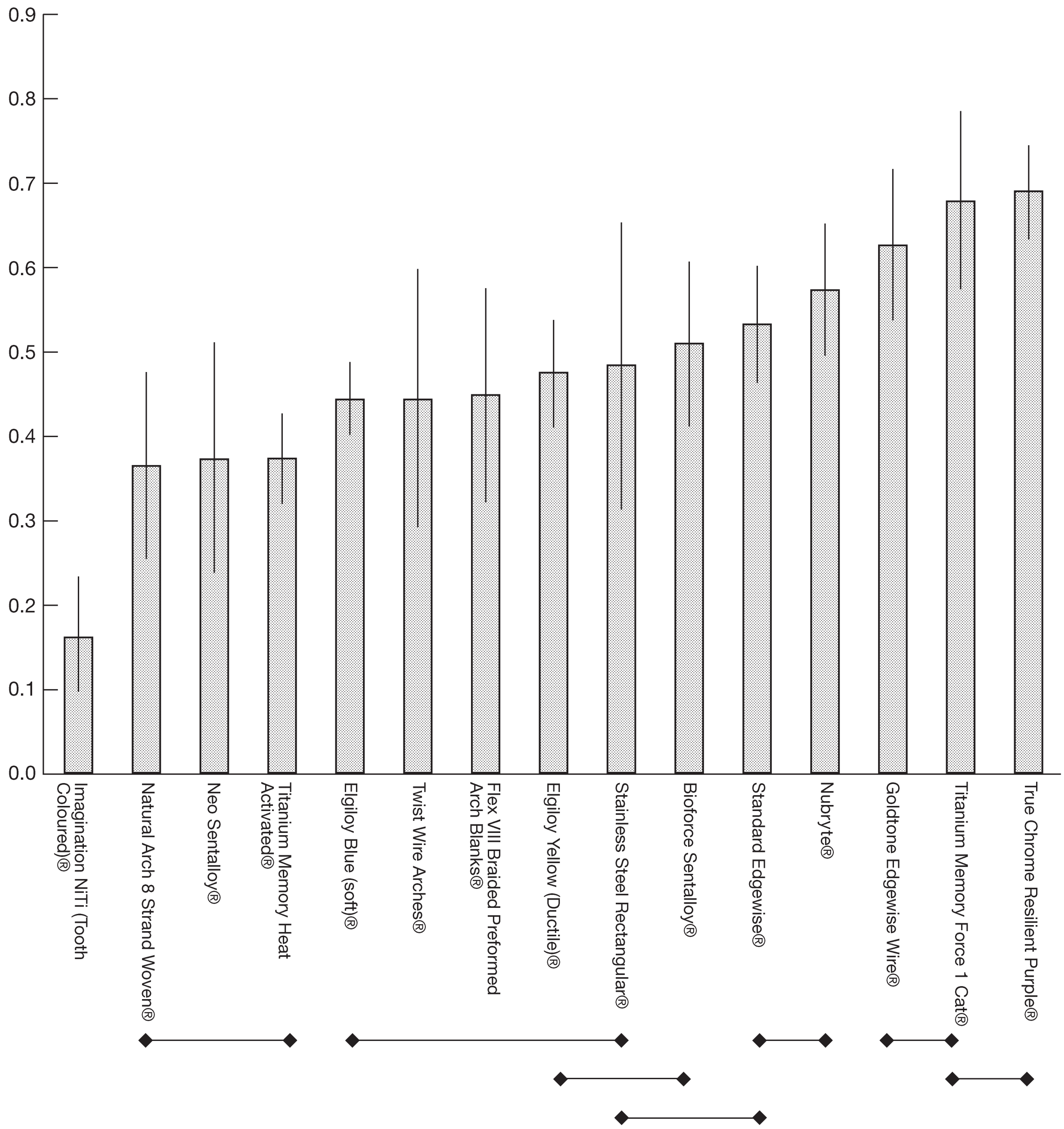

Figure 1 Means and standard deviations of the coefficient of friction of the different wires tested. The horizontal lines under the graph show the statistically different groups. Within a group, there was no statistical difference ($P \geq 0.05$).

semi-automated centred positioning of the wire into the bracket slot was performed. It was also possible to maintain the amount of clearance between the wall of the bracket slot and the surface of the wire. This means that contact between the bracket and archwire was only at the bracket base and the opposing 0.017 inch surface of the archwire. It would be difficult or even impossible to guarantee a constant F_N and also a centred positioning of the wire into the bracket slot when using elastic modules or even steel ligatures to tie the wires into the slot.

In many experimental studies on the quantitative determination of friction, the reported results are based on a single pass testing (Drescher *et al.*, 1989; Kusy *et al.*, 1992; Kuroe *et al.*, 1994; Tselepis *et al.*, 1994; Vaughan *et al.*, 1995; Yamaguchi *et al.*, 1996). In such set-ups, the bracket is drawn over a suspended archwire or vice versa unidirectionally, resulting in a continuous replenishment of wire material in a more or less steady state. Many of these investigations do not reflect the mode of frictional resistance that may actually occur in the oral cavity (Braun *et al.*, 1999). Various oral functions such as chewing, swallowing, speaking, etc., as well as the oral tissues contacting an orthodontic appliance, result daily in several thousand periodic, repetitive, and minute relative motions at the bracket–wire interface.

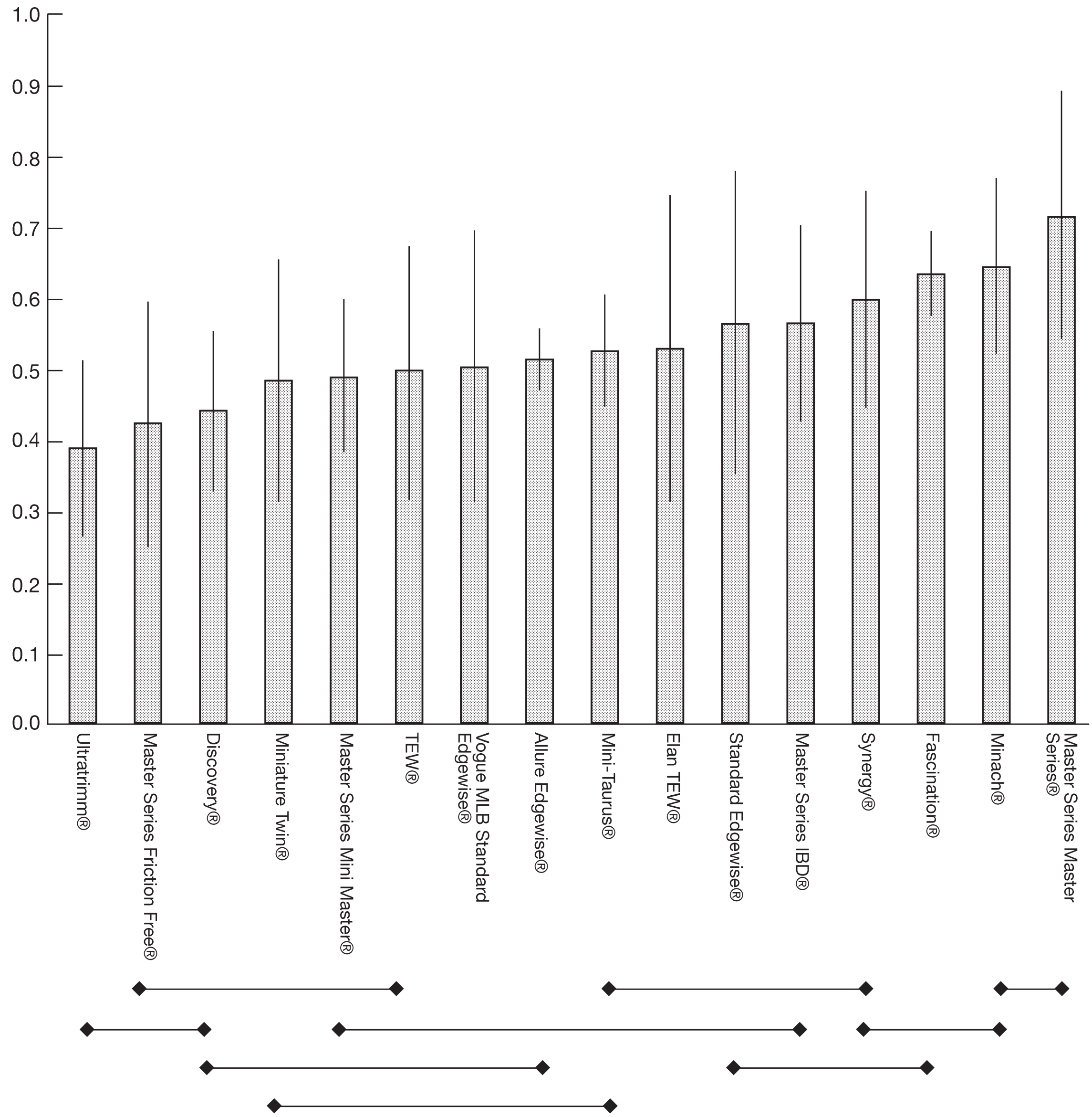

Figure 2 Means and standard deviations of the coefficient of friction of the different brackets tested. The horizontal lines under the graph show the statistically different groups. Within a group, there was no statistical difference ($P \geq 0.05$).

Therefore, a dynamic oscillating set-up better simulates the oral environment than a single pass test. The MTM fretting machine allows an oscillatory movement to be applied on to the bracket–wire combinations evaluated. That apparatus, calibrated specifically for this purpose (Willems *et al.*, 2001), is appropriate for the evaluation of the frictional properties of different bracket–wire combinations under dry dynamic contact conditions.

The data obtained for the COF are significantly higher than those reported in the orthodontic literature (Kusy and Whitley, 1990; Burstone and Farzin-Nia, 1995). They are, however, comparable with those in material engineering (Budinski, 1992). This may be explained by specific differences in the test set-up as well as by the so-called running-in phenomena (Willems *et al.*, 2001). Basically, it might be explained by the fact that in the single pass regime, there might be no destruction of the oxide layer on the outer surface of the stainless steel material. Indeed, it was recently demonstrated that in sliding wear, the native oxide layer present on stainless steel exposed to ambient air is not disrupted until a threshold normal load is reached (Garcia *et al.*, 2001). In single pass sliding tests a unidirectional movement is imposed on the contacting parts, and the metal surface of the wire in contact with the bracket base will always be new material which was not in contact with the bracket before and is still

Table 3 The mean force of friction (FOF), mean coefficient of friction (COF) and standard deviation (SD) in a 0.018 inch bracket slot using the centred positioning method.

Type	Mean FOF (N)	Mean COF	SD	Dimensions (inches)
Imagination NiTi (tooth coloured)	0.33	0.16	0.07	0.016 × 0.022
Neo Sentalloy	0.75	0.37	0.14	0.016 × 0.022
Bioforce Sentalloy	1.02	0.51	0.10	0.016 × 0.022
Titanium Memory Heat Activated	0.75	0.37	0.05	0.017 × 0.025
Twist Wire Arches	0.89	0.45	0.15	0.017 × 0.025
Standard Edgewise Wire	1.07	0.53	0.07	0.017 × 0.025
Goldtone Edgewise Wire	1.26	0.63	0.09	0.017 × 0.025
Natural Arch 8 Strand Woven	0.73	0.37	0.11	0.017 × 0.025
Nubryte	1.15	0.57	0.08	0.017 × 0.025
Titanium Memory Force 1 Cat	1.36	0.68	0.11	0.017 × 0.025
Flex VIII Braided Preformed Arch Blanks	0.90	0.45	0.13	0.017 × 0.025
True Chrome Resilient Purple	1.38	0.69	0.06	0.017 × 0.025
Elgiloy Blue (soft)	0.89	0.45	0.04	0.017 × 0.025
Elgiloy Yellow (ductile)	0.95	0.48	0.06	0.017 × 0.025
Stainless Steel Rectangular	0.97	0.49	0.17	0.017 × 0.025

Table 4 The mean force of friction (FOF), mean coefficient of friction (COF) and standard deviation (SD) on a 0.017 × 0.025 inch stainless steel wire using the centred positioning method.

Type	Material	Mean FOF (N)	Average COF	SD
Fascination	Ceramic	1.28	0.64	0.06
Vogue MLB Standard Edgewise	Ceramic	1.00	0.50	0.19
Allure Edgewise	Ceramic	1.04	0.52	0.04
Elan TEW	Ceramic + metal	1.06	0.53	0.22
Master Series Friction Free	Metal	0.84	0.42	0.17
Master Series Mini Master	Metal	0.98	0.49	0.11
Master Series IBD	Metal	1.14	0.57	0.14
Master Series Master Series	Metal	1.44	0.72	0.17
Ultratrimm	Metal	0.78	0.39	0.12
Discovery	Metal	0.88	0.44	0.11
TEW	Metal	1.00	0.50	0.18
Standard Edgewise	Metal	1.14	0.57	0.21
Minach	Metal	1.30	0.65	0.12
Mini-Taurus	Metal	1.06	0.53	0.08
Synergy	Metal	1.20	0.60	0.15
Miniature Twin	Metal	0.97	0.49	0.17

covered with an oxide layer that may act as a lubricant (Garcia *et al.*, 2001). In the oscillatory protocol of the MTM fretting machine, the wire surface moves back and forth at a lateral displacement amplitude of 200 μm and a frequency of 1 Hz. During the running-in phase of the fretting tests, a gradual destruction of the oxide layer takes place, as revealed by the progressive increase in F_F. This is explained by the fact that the sliding contact area between the wire and the bracket during fretting tests might not be sufficiently exposed to air to allow full re-oxidization to take place.

The stainless steel rectangular wire used in the calibration study was included in this evaluation and was found to exhibit a COF comparable with the results of the earlier investigation (Willems *et al.*, 2001). Also, the standard edgewise wire, which is another flat stainless steel wire, exhibited a COF that was not statistically significantly different from the former. For both flat stainless steel wires, the COF ranged between 0.49 and 0.53. A third flat stainless steel wire, the Nubryte, showed a COF that was statistically different from the stainless steel rectangular wire, but not from the standard edgewise wire. The small increase in COF noted with Nubryte may be due to different material or surface finishing treatment, compared with classic stainless steel wires.

The two Elgiloy wires included were cobalt–chromium–nickel alloys and displayed a COF comparable with the reference stainless steel rectangular wire. In fact, a significant difference was not found with this cobalt–chromium–nickel alloy, at least when its COF was considered.

The nickel–titanium wires showed a higher frictional resistance and, thus, in view of the constant normal load, also a higher COF. This is in agreement with the general findings in the literature, where it is reported that nickel–titanium wires exert a higher frictional resistance compared with normal stainless steel orthodontic wires (Kapila *et al.*, 1990; Kusy and Whitley, 1990). In this study, the low COF found for both Neo Sentalloy and Imagination NiTi may be attributed to differences in the stiffness of the wires and/or the elasticity of the evaluated materials. In addition, the latter was epoxy coated in order to simulate tooth colour and this coating might have contributed to the extremely low COF, namely 0.16. It was confirmed by the manufacturer that a depository process plates the base wire with epoxy resin of approximately 0.002 inches. With this procedure, a strong adhesion between the epoxy and the wire is achieved, preventing the wire sliding underneath the coating.

The findings related to the evaluated brackets confirm the reproducibility of the tests performed with the MTM fretting apparatus through the use of a standard bracket. Some stainless steel brackets such as TEW, Mini Master, Discovery and Master Series Friction Free displayed similar statistically insignificant results, with a COF ranging from 0.42 to 0.50. Other stainless steel brackets, on the contrary, such as the Master Series, showed a significantly higher COF of 0.72. Compared with the latter, the Master Series Friction Free showed a significant reduction in the COF, but was still statistically comparable with some of the other stainless steel brackets, such as Discovery and Ultratrimm. In fact, Ultratrimm showed the lowest mean COF of 0.39.

Another important finding is that, although some of the evaluated ceramic brackets, e.g. Allure Edgewise and Vogue MLB Standard Edgewise, showed a slightly higher COF, they still remained statistically comparable with the reference and other stainless steel brackets. However, ceramic brackets, such as Fascination, displayed a significantly higher COF of 0.64. This means that there is no contraindication to ceramic brackets for reasons of friction when appropriate material selection and evaluation have been performed. Elan TEW, a plastic bracket with a ceramic reinforcement and a metal slot insert, also exhibited a COF of 0.53, comparable with most of the previously mentioned brackets, although it was significantly different from the Miniature Twin reference bracket, Discovery, Master Series Friction Free and Ultratrimm.

Conclusion

The frictional behaviour of orthodontic materials was evaluated by simulating the dynamics between archwire and brackets, using a fretting test apparatus. Knowledge of the type of wire or bracket or combinations which provide a lower or higher dynamic COF can assist in selecting the optimum material for sliding and non-sliding mechanics. Such an in-depth investigation of friction at a micro- and nano-level can assist in the development of new wires generating lower friction.

From this fretting study performed in ambient air at 50 per cent relative humidity, it can be concluded that among the wire–bracket combinations investigated, the lowest friction was achieved with an epoxy-coated wire and a stainless steel bracket. In that case, the contact between bracket and wire is not metal–metal, characterized by a large risk of adhesive wear, but a plastic–metal contact where the plastic may provide some lubrication. Concerning bracket evaluation, it can be concluded that a comparable ranking of the materials tested was obtained, and that some of the ceramic brackets displayed a reasonable COF.

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