

COMPARISON OF SURFACE ROUGHNESS AND FRICTIONAL FORCES OF VARIOUS BRACKET AND ARCHWIRE COMBINATIONS – AN IN VITRO STUDY

Running title: Surface roughness and friction of bracket–archwire combinations

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Abstract

Frictional resistance at the bracket–archwire interface opposes tooth movement during sliding mechanics and is influenced by the surface roughness of the materials in contact. This in vitro study compared the surface roughness and the static and kinetic frictional forces of pre-adjusted edgewise Stainless Steel and Cobalt-Chromium brackets coupled with Stainless Steel, Elgiloy and Titanium-Molybdenum Alloy archwires, before and after subjecting them to friction. Ninety brackets and ninety archwires were tested in six combinations of fifteen samples each. Friction was measured on a Universal Testing Machine in the dry state. Surface topography of the bracket slots and the wires was examined by Scanning Electron Microscopy and quantified with a non-contact optical profilometer. Static friction exceeded kinetic friction in every combination. The Cobalt-Chromium bracket with Stainless Steel archwire produced the least friction and the Stainless Steel bracket with Titanium-Molybdenum Alloy archwire the most. Cobalt-Chromium brackets were rougher than Stainless Steel brackets, and Titanium-Molybdenum Alloy wires were roughest, both before and after friction; roughness increased in every combination after sliding. Archwire material influenced frictional behaviour more than bracket material, and the Cobalt-Chromium bracket with Stainless Steel archwire appears the most favourable combination for sliding mechanics, especially in nickel-sensitive patients.

INTRODUCTION

During sliding mechanics, the archwire slides through the bracket slot, and the frictional resistance generated at this interface opposes every force applied to move a tooth (Fidalgo et al., 2011). This resistance appears as static friction, which impedes the initiation of movement, and as kinetic friction, which resists continued sliding. Archwire cross-section, bracket design, material

composition and slot dimensions together determine its magnitude (Kopsahilis and Drescher, 2022). Excessive friction reduces the efficiency of tooth movement and demands higher force levels that may compromise the periodontium (Nair et al., 2012).

Surface roughness of the contacting materials is a principal determinant of friction, since real contact occurs only at

surface asperities (Doshi and Bhad-Patil, 2011). Roughness reflects the alloy itself and its manufacturing and polishing history, and rises further during intraoral ageing through biofilm accumulation, electrochemical corrosion, prophylactic abrasion and repetitive wear at the bracket–wire interface (Aliaga-Del Castillo et al., 2019).

Stainless Steel archwires in Stainless Steel brackets remain the conventional standard for their low friction (Doshi and Bhad-Patil, 2011), but concern over the nickel content of Stainless Steel has prompted interest in alternative alloys (Fidalgo et al., 2011). Cobalt-Chromium brackets offer a smoother finish and reduced nickel ion release, while Titanium-Molybdenum Alloy wires combine elasticity and reduced stiffness (Kopsahilis and Drescher, 2022), yet react against dissimilar alloys, accelerating abrasive wear (Cacciafesta et al., 2003). Data on Cobalt-Chromium brackets combined with different archwire alloys nevertheless remain scarce. This study was therefore undertaken to evaluate and compare the surface roughness and the static and kinetic frictional forces of Stainless Steel and Cobalt-Chromium brackets coupled with Stainless Steel, Elgiloy and Titanium-Molybdenum Alloy archwires, before and after subjecting them to friction.

MATERIALS AND METHODS

Ninety pre-adjusted edgewise maxillary right canine brackets of MBT prescription with a 0.022×0.028 -inch slot were tested: 45 Stainless Steel (Leone, Italy) and 45 Cobalt-Chromium (TP Orthodontics, Indiana, USA). Ninety straight archwires of 0.019×0.025 inch were tested: 30 Stainless Steel (Orthometric, Brazil), 30 Elgiloy (RMO, USA) and 30 Titanium-Molybdenum Alloy (Morelli, Brazil). Brackets formed two groups by material- Group 1 consisting Stainless Steel brackets and

Group 2 consisting Cobalt Chromium brackets and each group three subgroups by archwire material- A- Stainless Steel archwires, B-Elgiloy archwires, C- TMA archwires, giving six combinations of 15 samples each. The study was carried out in three phases: surface roughness in the as-received condition (SR_0), static friction (F_0) & kinetic friction (F_1) and surface roughness after friction (SR_1).

Sample preparation

Following the models of Doshi and Bhad-Patil (2011) and Nair et al. (2012), test models of $150 \times 20 \times 3$ mm were fabricated from clear acrylic sheet (Bigimall, India) and colour coded with acrylic paint (Fevicryl, Pidilite, India): yellow for Stainless Steel brackets and blue for Cobalt-Chromium brackets. A fine line scribed along the central axis of each jig guided reproducible bracket positioning. Because the in-built tip and torque of pre-adjusted brackets confound frictional measurement, 6 cm segments of 0.021×0.025 -inch Stainless Steel wire (Metro Orthodontics, India) were passively seated in each slot and ligated with elastomeric modules (Captain Ortho, India) before bonding, following Thomas et al. (1998). Brackets were bonded with cyanoacrylate adhesive (Pidilite, India), and 10 cm archwire segments were ligated with 0.009-inch Stainless Steel ligature wire (Jaypee, India) using a Mathieu plier (GDC Orthodontics, India).

Phase I – Evaluation of surface roughness in as-received condition

Surface morphology was examined by field emission scanning electron microscopy (SEM; JEOL JCM-6000 Plus benchtop) at 15 kV and $\times 500$ magnification, following Doshi and Bhad-Patil (2011). Roughness was quantified with a non-contact optical profilometer (Bruker ContourX; Fig. 3a) using white light interferometry with a

helium–neon beam of 633 nm, yielding the areal roughness parameter S_a , the arithmetical mean height of the surface, for the slot floor and the wire, as adopted by Choi et al. (2014) and Agarwal et al. (2016). Profiles were levelled using Bruker software and extreme peaks and valleys excluded. Every bracket slot and archwire was measured in this condition before any friction testing, and the values recorded as SR_0 .

Phase II – Evaluation of static and kinetic friction (F_0 and F_1)

Friction was measured on a Universal Testing Machine (Instron, USA; Fig. 3b) in the dry state at room temperature. Each bracket was tested once and each archwire drawn across a single bracket, eliminating the influence of wear. The assembly was mounted vertically in the jaws of the machine so that the wire passed through the slot without angular discrepancy. Following Cacciafesta et al. (2003), the crosshead speed was 5 mm/min with a 10 N load cell calibrated over 0–10 N. Static friction was taken as the peak of the force–distance curve; kinetic friction was recorded at 1 mm intervals along the remaining wire length, giving nine readings per sample whose mean represented the kinetic friction of that combination.

Phase III – Evaluation of surface roughness after subjecting to friction (SR_1)

On completion of friction testing, the same 90 bracket slots and 90 archwires were retrieved and re-examined, so that each specimen served as its own control and the before-and-after values could be compared pairwise. Surface morphology was re-examined by Scanning Electron Microscopy and roughness re-quantified with the non-contact optical profilometer, using settings, scanning speed, levelling and thresholding identical to those of Phase I, and the values recorded as SR_1 . No specimen was tested more than once at any stage, so that the change from SR_0 to SR_1 reflected a single episode of sliding.

Statistical analysis

Data were analysed by one-way analysis of variance (ANOVA) with post hoc Tukey's test, and by paired t-test for before-and-after comparison of roughness. $p < 0.05$ was considered significant.

RESULTS

Static and kinetic friction differed highly significantly among the six combinations ($p < 0.001$; Table 1, Fig. 1). Subgroup IC recorded the highest and subgroup IIA the lowest values of both, and static friction exceeded kinetic friction in every combination. Post hoc comparison showed significant differences for every subgroup pair within groups ($p < 0.001$; Table 1).

Table 1: Mean and standard deviation of static (F_0) and kinetic (F_1) friction of Stainless Molybdenum Alloy archwires.

Group	Subgroup	Static friction F_0		Kinetic friction F_1	
		Mean $\pm$ SD (N)	p value	Mean $\pm$ SD (N)	p value
I	IA	0.1910 $\pm$ 0.00515	0.000*	0.1515 $\pm$ 0.00409	0.000*
	IB	0.3295 $\pm$ 0.00792	0.000*	0.2843 $\pm$ 0.00583	0.000*
	IC	0.4884 $\pm$ 0.00613	0.000*	0.3525 $\pm$ 0.00820	0.000*
II	IIA	0.1294 $\pm$ 0.00553	0.000*	0.1197 $\pm$ 0.00602	0.000*
	IIB	0.2251 $\pm$ 0.00719	0.000*	0.1779 $\pm$ 0.00936	0.000*
	IIC	0.3525 $\pm$ 0.01062	0.000*	0.2740 $\pm$ 0.01099	0.000*

One-way ANOVA: $F_{0f} = 4725.4$, $P < 0.001$; $F_{1f} = 2029.7$, $P < 0.001$. SD = standard deviation.

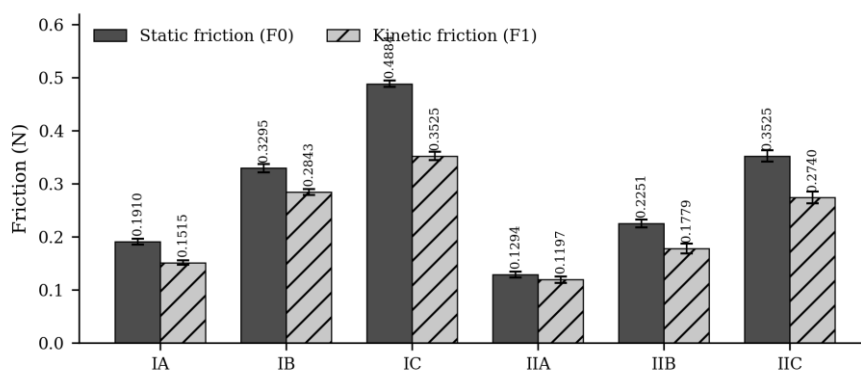


Fig. 1: Mean and standard deviation of static (F₀) and kinetic (F₁) friction of each bracket–archwire combination.

Stainless Steel brackets were smooth and homogeneous as received and showed only fine superficial scratches after friction, whereas Cobalt-Chromium brackets presented prominent ridges, micro-pits and irregular asperities before friction and pronounced grooves, pitting and irregular wear tracks afterwards (Fig. 5).

Among the archwires (Fig. 5), Stainless Steel was smooth and uniform initially

and minimally altered after friction. Elgiloy showed moderate irregularities and shallow grooves as received and moderate wear tracks afterwards. Titanium-Molybdenum Alloy displayed pronounced micro-pits and irregular asperities before friction and severe degradation with deep grooves, ploughing marks and surface tearing afterwards.

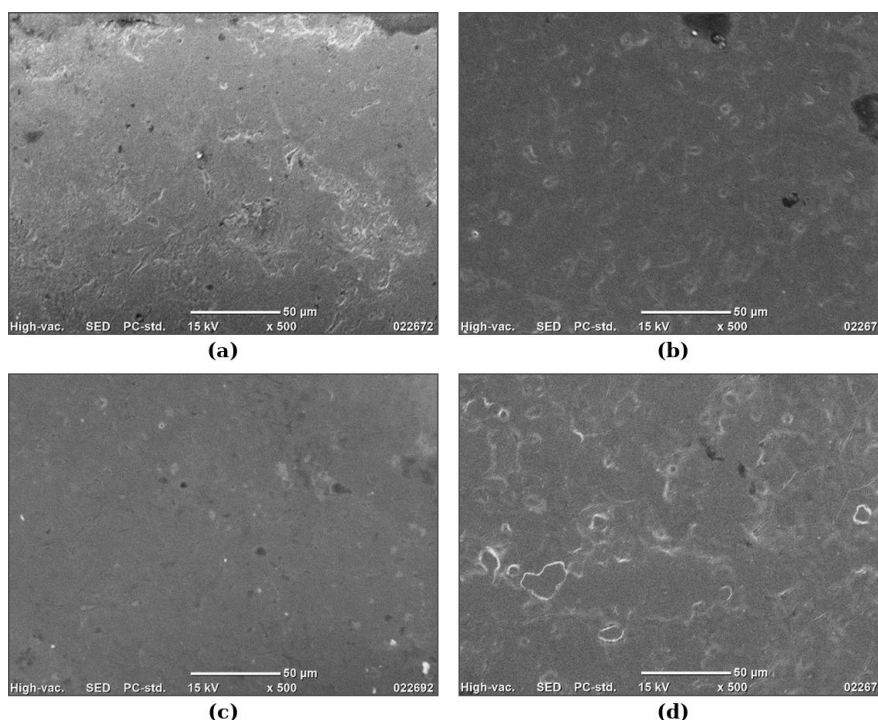


Fig. 4: Scanning electron micrographs of bracket slots (×500), before & after friction

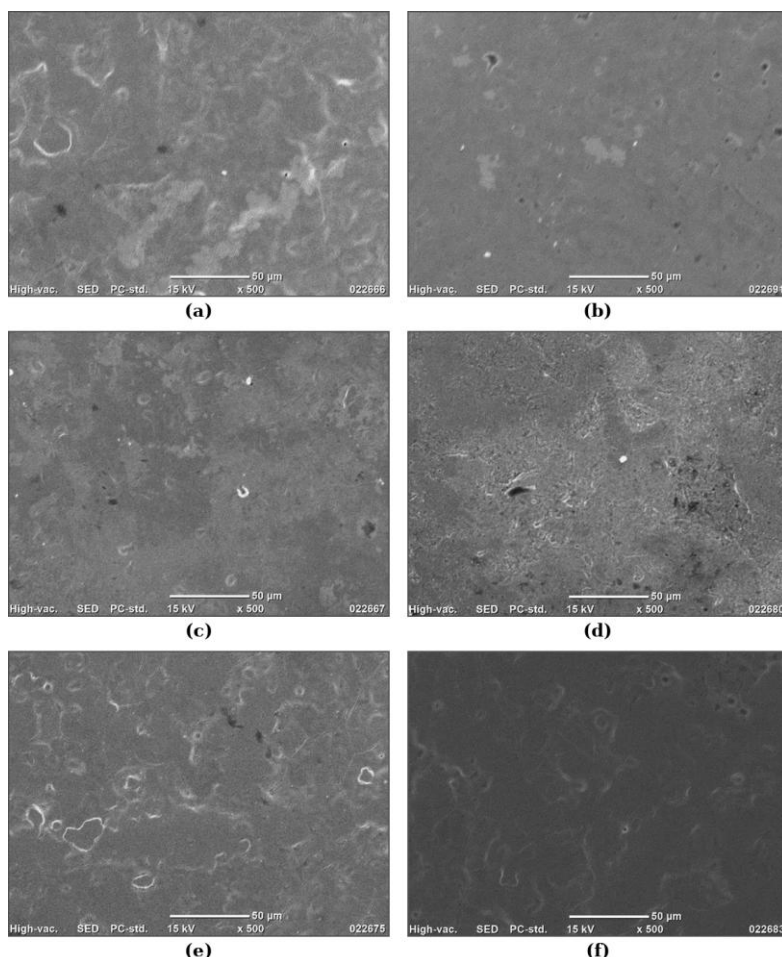


Fig. 5: Scanning electron micrographs of archwire surfaces ($\times 500$), before & after friction

Profilometric findings corroborated with SEM findings. Surface roughness increased in every subgroup after friction, significantly so for brackets in subgroups IA, IC and IIA only, whereas the increase in archwire roughness was non-significant in all subgroups (Tables 2 and 3, Figs. 5 and 6). Comparison within groups showed no significant

differences for either brackets or archwires, before or after friction ($p > 0.05$; Tables 2 and 3). Between groups, bracket roughness differed significantly at several pairs without a consistent hierarchy (Table 2), while archwire roughness was non-significant before friction and significant for every pair after friction except IB (Table 3).

Table 2: Mean and standard deviation, t value, p value of surface roughness of Stainless Steel and Cobalt-Chromium brackets before (SR_0) and after (SR_1) subjecting to friction.

Group	Subgroup	SR_0 (μm), Mean $\pm$ SD	SR_1 (μm), Mean $\pm$ SD	t value	p value
I	IA	0.2615 ± 0.01344	0.3655 ± 0.01202	-1.040	0.005*
	IB	0.2910 ± 0.03960	0.3540 ± 0.04950	-1.000	0.500
	IC	0.3155 ± 0.02330	0.4280 ± 0.02263	-225.000	0.003*
II	IIA	0.4930 ± 0.05091	0.6695 ± 0.05869	-32.091	0.002*
	IIB	0.4790 ± 0.00424	0.5975 ± 0.00495	-18.231	0.035*
	IIC	0.5005 ± 0.02192	0.6170 ± 0.15839	-1.207	0.440

Paired t-test; * $p < 0.05$ significant.

Table 3: Mean and standard deviation, t value, p of surface roughness of Stainless Steel, Elgiloy and Titanium-Molybdenum Alloy archwires before (SR₀) and after (SR₁) subjecting to friction.

Group	Subgroup	SR ₀ (μm), Mean ± SD	SR ₁ (μm), Mean ± SD	t value	p value
I	IA	0.1775 ± 0.00251	0.2220 ± 0.00269	-9.889	0.060
	IB	0.1700 ± 0.00212	0.2350 ± 0.00156	-16.250	0.039*
	IC	0.2425 ± 0.00629	0.2890 ± 0.00127	-0.869	0.544
II	IIA	0.3620 ± 0.00396	0.5055 ± 0.00919	-6.674	0.090
	IIB	0.3695 ± 0.00276	0.4895 ± 0.00304	-2.927	0.210
	IIC	0.3885 ± 0.00460	0.5120 ± 0.00990	-4.843	0.130

Paired t-test; *P < 0.05 significant.

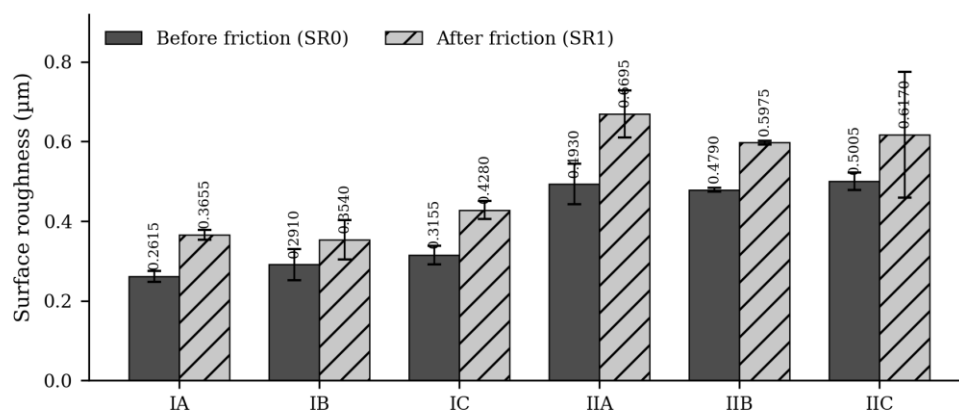


Fig. 2: Mean and standard deviation of bracket surface roughness before (SR₀) and after (SR₁) friction.

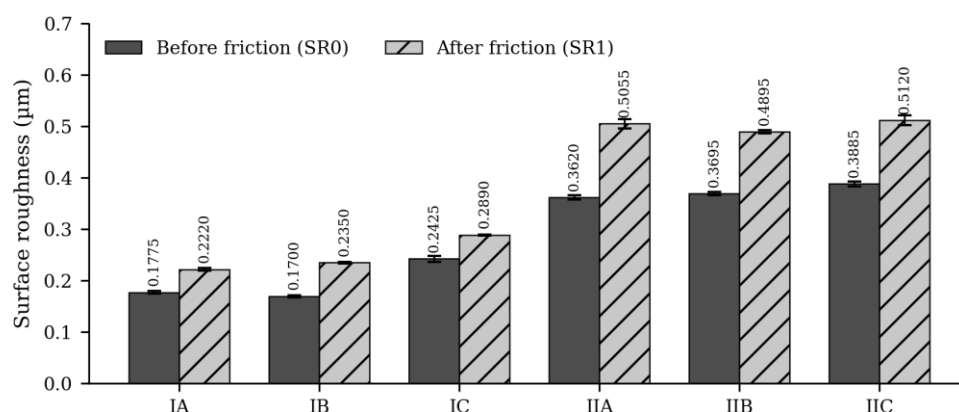


Fig. 3: Mean and standard deviation of archwire surface roughness before (SR₀) and after (SR₁) friction.

DISCUSSION

An in vitro design permits control of bracket positioning, ligation, wire dimension and testing environment that cannot be achieved clinically, and affords the reproducibility required to

compare frictional characteristics of orthodontic materials (Angolkar et al., 1990; Downing et al., 1995; Fidalgo et al., 2011). The 0.022 × 0.028 inch slot was chosen as the most widely used clinically, and 0.019 × 0.025 inch wires because this dimension is routine during retraction (Angolkar et al., 1990). Khalid et al. (2012) observed that

frictional resistance is largely independent of wire stiffness and cross-sectional area but is influenced by wire geometry, rectangular wires being preferred for sliding mechanics.

SEM was preferred for qualitative assessment for its resolution and depth of field, which permit detection of micro-defects within the slot beyond the capacity of optical inspection (Doshi and Bhad-Patil, 2011). For quantification, contact stylus profilometry evaluates deviation along a single trace and may itself alter the surface, and atomic force microscopy, though capable of nanometre-scale resolution (Mohan and Jain, 2022), is limited by small scan area and cost. Non-contact white light interferometry was therefore used, offering areal scanning and nanometre repeatability (Choi et al., 2014; Agarwal et al., 2016).

The highest friction, in the Stainless Steel bracket–Titanium-Molybdenum Alloy wire pair, is attributable to increased binding of the Stainless Steel slot together with the high load-deflection rate and elasticity intrinsic to Titanium-Molybdenum Alloy; comparable findings were reported by Sahany and Kumar (2020) and, for kinetic friction in the same pairing, by Fidalgo et al. (2011). The lowest friction, in the Cobalt-Chromium bracket–Stainless Steel wire pair, reflects the smoother finish of Cobalt-Chromium brackets and the burnishing tendency of Stainless Steel wires, in agreement with Obaid and Al-Dabagh (2020)¹⁶. That static friction exceeded kinetic friction throughout reflects the transition from initial binding to dynamic resistance once motion is established. Archwire material thus determined the magnitude of frictional resistance, whereas bracket material principally influenced the gap between static and kinetic friction.

The smoother as-received Stainless Steel surface is explicable by refined finishing

and fine grain structure, consistent with Pratten et al. (1990), while the asperities of Cobalt-Chromium reflect a heterogeneous alloy microstructure and different polishing procedures (Redlich et al., 2003; Obaid and Al-Dabagh, 2020). The high roughness of Titanium-Molybdenum Alloy is attributable to its oxide layer and microstructural irregularity (Bourauel et al., 1998), whereas Stainless Steel was smoothest owing to its polished surface and alloy homogeneity (Kopsahilis and Drescher, 2022). After sliding, the faint striations of Stainless Steel indicate better resistance to abrasive wear (Pratten et al., 1990), while the grooves and pitting of Cobalt-Chromium suggest greater susceptibility to surface modification (Moore et al., 2004); that the difference between them remained non-significant indicates comparable wear mechanisms despite differing initial morphology (Redlich et al., 2003). The deep grooves and tearing of Titanium-Molybdenum Alloy are consistent with asperity fracture, ploughing and disruption of the oxide layer (Bourauel et al., 1998); Elgiloy showed controlled wear with limited damage accumulation (Sahany and Kumar, 2020) and Stainless Steel preserved its surface integrity (Shaik, 2021).

Clinically, the low frictional resistance of the Cobalt-Chromium bracket–Stainless Steel wire combination suits procedures in which reduced resistance to sliding is desirable, particularly space closure and retraction, and offers a useful alternative in patients with nickel hypersensitivity. The higher friction of Titanium-Molybdenum Alloy wires warrants consideration of the increased resistance and anchorage demands when they are used in friction-dependent mechanics. These findings are limited by an in vitro design that could not reproduce the oral environment, the tip, torque and occlusal loading encountered clinically, or long-term wear; in vivo

studies and comparisons extending to further bracket types, ligation methods and newer alloys are required to confirm them (Vartolomei et al., 2022)²¹.

Within these limitations it is concluded that static friction exceeded kinetic friction in all combinations; that the Stainless Steel bracket–Titanium-Molybdenum Alloy wire combination generated the highest and the Cobalt-Chromium bracket–Stainless Steel wire combination the lowest friction; that Cobalt-Chromium brackets were rougher than Stainless Steel brackets and Titanium-Molybdenum Alloy wires roughest, both before and after friction; that roughness increased in all brackets and wires after sliding; and that archwire material exerted a greater influence than bracket material.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FUNDING

Self-funded.

ETHICAL STATEMENT

This was an in vitro investigation on commercially available brackets and archwires; no human participants, human tissue or animals were involved, and informed consent and animal ethics clearance were not applicable. The protocol was approved by the Institutional Ethics Committee of C. K. S. Theja Institute of Dental Sciences and Research, Tirupati [CKS/ORTHO/23-24/05 , 04/04/2024].

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