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Comparative Evaluation of Frictional Resistance of Zinc Oxide Nanoparticle-Coated Ceramic Brackets and Esthetic Archwires in Dry and Wet Environments: An In Vitro Study

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Abstract: Background: Friction at the bracket-archwire interface can reduce the effective orthodontic force delivered during sliding mechanics, and this problem may be accentuated when esthetic ceramic brackets and coated archwires are used. Zinc oxide (ZnO) nanoparticle surface modification may improve sliding behavior while preserving an esthetic appearance. Objective: To evaluate and compare the coefficient of friction of ZnO nanoparticle-coated and non-coated ceramic brackets and epoxy-coated esthetic stainless-steel archwires under dry and artificial-saliva conditions. Methods: A comparative in vitro experiment used 136 bracket-wire specimens allocated to eight groups (n=17 each) according to bracket coating, archwire coating, and testing medium. ZnO coating was produced by a dip-coating protocol. Friction was measured using a universal testing machine with a 10-N load cell at a crosshead speed of 0.5 mm/min. Data were analyzed using one-way ANOVA, Bonferroni post-hoc comparisons, and independent-samples t tests. Results: Mean coefficient of friction ranged from 0.44±0.02 in the uncoated bracket/uncoated wire dry group to 0.17±0.02 in the coated bracket/coated wire artificial-saliva group. Intergroup differences were significant ($F=313.96$, $p<0.001$). Pooled analysis showed lower friction with coated versus uncoated ceramic brackets (0.24±0.06 vs 0.34±0.08; $p<0.001$), coated versus non-coated epoxy archwires (0.23±0.05 vs 0.35±0.07; $p<0.001$), and artificial saliva versus dry testing (0.26±0.08 vs 0.31±0.09; $p=0.001$). Conclusion: ZnO nanoparticle coating significantly reduced friction in the tested esthetic orthodontic system, with the lowest values when both the ceramic bracket and epoxy archwire were coated and tested in artificial saliva. These findings support further evaluation of ZnO-modified esthetic appliances under clinically representative conditions.

Keywords: Zinc oxide nanoparticles; ceramic brackets; esthetic archwires; frictional resistance; artificial saliva; orthodontics

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INTRODUCTION

Sliding mechanics is widely used during orthodontic space closure and alignment because it permits controlled movement of teeth along an archwire. A clinically important limitation of this approach is friction at the bracket-wire interface, which opposes the applied force and may reduce the amount of force available for biologic tooth movement. In vitro investigations have consistently shown that bracket design and material affect frictional behavior, and ceramic brackets may generate greater resistance than some conventional or self-ligating systems **[1]**. Contemporary interpretation of resistance to sliding also recognizes the contribution of binding and notching, particularly when the wire contacts the bracket corners during angulation **[2]**. Geometric relationships between bracket slot dimensions, wire dimensions, and the critical contact angle further determine whether classical friction or binding dominates the sliding process **[3]**.

The growing demand for less visible fixed appliances has increased the use of ceramic brackets and tooth-colored or polymer-coated archwires. Ceramic brackets, however, possess surface characteristics that can adversely affect sliding. Angolkar et al. demonstrated greater friction with ceramic brackets than with stainless-steel brackets across several orthodontic wire alloys **[4]**, while surface-roughness studies have shown that the tribologic response depends on the specific bracket-wire combination **[5]**. At the same time, patient preference for discreet appliances has encouraged continued development of esthetic wires; epoxy and other coated wires are used because of their favorable appearance, although their mechanical performance may be influenced by coating integrity and surface roughness **[6]**, **[7]**.

Nanotechnology offers a strategy for modifying these interfaces without abandoning an esthetic appliance design. Zinc oxide is particularly relevant because of its white appearance, biocompatibility, surface-modifying potential, and broad dental applications **[8]**, **[9]**. Experimental work has demonstrated that ZnO nanoparticle deposition on orthodontic wires can substantially reduce friction, with the magnitude of reduction depending on wire dimension and coating characteristics **[10]**. More recent work on nano-coated bracket-wire configurations also supports the possibility that surface modification can alter frictional resistance in orthodontic systems **[11]**. Nevertheless, previous studies have produced heterogeneous findings, and the combined effect of coating both a ceramic bracket and an esthetic epoxy-coated wire, particularly in both dry and simulated oral environments, remains insufficiently defined.

The present study therefore evaluated the coefficient of frictional resistance of ZnO nanoparticle-coated and non-coated ceramic brackets combined with ZnO nanoparticle-coated and non-coated epoxy esthetic stainless-steel archwires in dry and artificial-saliva conditions. The primary aim was to determine whether coating the bracket, the archwire, or both components significantly reduced friction, and whether the testing medium modified this effect.

Materials and Methods

Study design and setting. A comparative experimental in vitro study was conducted in the Department of Orthodontics and Dentofacial Orthopaedics, Nims Dental College and Hospital, Nims University Rajasthan, Jaipur, over 1.5 years. The experiment was designed as an eight-group factorial comparison incorporating two bracket surface conditions (non-coated and ZnO nanoparticle-coated), two epoxy archwire surface conditions (non-coated and ZnO nanoparticle-coated), and two testing environments (dry and artificial saliva).

Sample size and grouping. The sample-size calculation was based on expected differences in frictional resistance between comparison groups using a 95% confidence level and 80% statistical power. The calculated minimum was 16.85 specimens per group, rounded to 17. A total of 136 commercially available orthodontic bracket-wire specimens were therefore included, with 17 independent specimens in each of eight groups. The tested components were 0.022 x 0.028-inch MBT ceramic brackets for maxillary canines and 0.019 x 0.025-inch epoxy-coated esthetic stainless-steel archwires. Each wire segment measured 2.5 cm.

Eligibility criteria. Included materials were commercially available epoxy-coated esthetic stainless-steel archwires, ceramic maxillary canine brackets, standard elastic ligatures, and artificial saliva. Conventional metal brackets, conventional non-esthetic archwires, previously used or recycled ceramic brackets, self-ligating bracket systems, and metal ligature wires were excluded. Each bracket and wire segment was used for only one friction test to avoid a wear-related carry-over effect.

ZnO nanoparticle coating procedure. Before coating, the specimens were rinsed with distilled water, ultrasonicated in ethanol for 10 minutes, rinsed again, and air-dried. Surface activation was performed by immersion in 1 M sodium hydroxide for 30 minutes, followed by thorough rinsing and drying at room temperature. For preparation of the coating suspension, 0.5 g chitosan was dissolved in 100 mL of 1% acetic acid and stirred for 2-3 hours. Approximately 0.5-1 g of 99.9% pure ZnO nanoparticles was added, the suspension was ultrasonicated for 30 minutes to limit agglomeration, and the pH was adjusted to 5-6. Brackets and wire segments assigned to the coated conditions were immersed completely in the suspension for 2-5 minutes, withdrawn at a constant slow speed, hung vertically for 30 minutes, and cured in a hot-air oven at 60°C for 1 hour. After cooling, samples were stored in sterile airtight containers at room temperature until testing.

Friction testing. Four bracket-wire surface combinations were evaluated in both dry and wet environments. Brackets were bonded to a glass plate with cold-cure epoxy resin adhesive and positioned vertically in the universal testing machine. A calibrated 10-N load cell was used. In wet groups, mucin-based artificial saliva was applied evenly over the bracket and wire with a dropper. Each wire was drawn once through its bracket while the crosshead moved at 0.5 mm/min. Frictional force was recorded continuously, and the peak value on the generated graph was used as the friction measurement for the specimen.

Statistical analysis. Data were compiled in Microsoft Excel and analyzed in IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Group means and standard deviations were calculated. One-way analysis of variance (ANOVA) assessed differences among the eight experimental groups, followed by Bonferroni-adjusted post-hoc comparisons. Independent-samples t tests compared pooled friction values according to ceramic-bracket coating, epoxy-archwire coating, and testing medium. Cohen's d was reported for the pooled comparisons. Statistical significance was set at $p<=0.05$.

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RESULT

All 136 specimens were included in the analysis. The overall mean coefficient of friction was 0.29±0.09. A clear gradient was observed across the eight groups: the highest mean occurred in Group A, representing non-coated brackets and non-coated archwires in the dry environment (0.44±0.02), whereas the lowest mean occurred in Group H, in which both components were ZnO nanoparticle-coated and tested in artificial saliva (0.17±0.02). One-way ANOVA confirmed a highly significant overall difference among the groups ($F=313.96$, $p<0.001$) (Table 1).

Table 1. Coefficient of friction across the eight experimental groups

Group	Ceramic bracket	Epoxy archwire	Medium	n	Coefficient of friction (mean ± SD)
A	Non-coated	Non-coated	Dry	17	0.44 ± 0.02
B	Non-coated	Non-coated	Artificial saliva	17	0.37 ± 0.02
C	Non-coated	ZnO nano-coated	Dry	17	0.30 ± 0.02
D	Non-coated	ZnO nano-coated	Artificial saliva	17	0.25 ± 0.02
E	ZnO nano-	Non-coated	Dry	17	0.32 ± 0.02

Group	Ceramic bracket	Epoxy archwire	Medium	n	Coefficient of friction (mean ± SD)
	coated				
F	ZnO nano-coated	Non-coated	Artificial saliva	17	0.27 ± 0.02
G	ZnO nano-coated	ZnO nano-coated	Dry	17	0.20 ± 0.02
H	ZnO nano-coated	ZnO nano-coated	Artificial saliva	17	0.17 ± 0.02
Overall	-	-	-	136	0.29 ± 0.09

Bonferroni post-hoc analysis showed that most pairwise comparisons were statistically significant. The largest contrast was between Groups A and H (mean difference 0.28, p<0.001). The A-B comparison showed that artificial saliva reduced friction even when both components were non-coated (mean difference 0.07, p<0.001). The C-F comparison was the only reported pair that did not reach the 0.05 significance level (mean difference 0.02, p=0.074) (Table 2).

Table 2. One-way ANOVA and selected Bonferroni post-hoc comparisons

Comparison	Mean difference	SE	p-value	95% CI
Overall ANOVA	-	-	<0.001	F=313.96; df=7,128
A vs B	0.07	0.01	<0.001	0.05 to 0.09
A vs C	0.15	0.01	<0.001	0.13 to 0.17
A vs H	0.28	0.01	<0.001	0.25 to 0.30
C vs F	0.02	0.01	0.074	-0.00 to 0.05
G vs H	0.03	0.01	0.001	0.01 to 0.06

When data were pooled by individual experimental factor, ZnO coating produced substantial reductions in friction. Nano-coated ceramic brackets had a lower mean coefficient than non-coated brackets (0.24±0.06 vs 0.34±0.08; t=8.12, p<0.001; Cohen's d=1.39). Similarly, nano-coated epoxy archwires had lower friction than non-coated epoxy archwires (0.23±0.05 vs 0.35±0.07; t=12.12, p<0.001; Cohen's d=2.08). Artificial saliva also reduced friction relative to dry conditions (0.26±0.08 vs 0.31±0.09; t=3.44, p=0.001; Cohen's d=0.59) (Table 3).

Table 3. Pooled comparisons according to coating and testing medium

Factor	Group 1 (mean ± SD)	Group 2 (mean ± SD)	t	p-value	Cohen's d
Ceramic bracket	Non-coated: 0.34 ± 0.08	ZnO coated: 0.24 ± 0.06	8.12	<0.001	1.39
Epoxy archwire	Non-coated: 0.35 ± 0.07	ZnO coated: 0.23 ± 0.05	12.12	<0.001	2.08
Testing medium	Dry: 0.31 ± 0.09	Artificial saliva: 0.26 ± 0.08	3.44	0.001	0.59

DISCUSSION

The present in vitro study demonstrated that ZnO nanoparticle surface modification significantly altered the frictional behavior of an esthetic orthodontic bracket-wire system. The combination of a nano-coated ceramic bracket and nano-coated epoxy archwire in artificial saliva produced the lowest coefficient of friction, while the corresponding fully non-coated combination in the dry environment produced the highest value. The large overall ANOVA effect, together with the pooled reductions for bracket coating and archwire coating, indicates that the observed difference was not confined to a single experimental combination.

The reduction associated with ZnO-coated archwires is consistent with the experimental findings of Kachoei et al. **[10]**, who reported substantial decreases in friction after ZnO nanoparticle deposition on stainless-steel wires. Their results were particularly pronounced for 0.019 x 0.025-inch wires, a dimension comparable with that used in the present experiment. A plausible explanation is that nanoparticle deposition modifies surface topography and reduces direct interlocking between microscopic asperities. Related nanocoating research has also shown that carefully engineered nanoparticle films can produce marked reductions in frictional coefficients at metallic interfaces **[17]**. These observations support the concept that nanoscale surface modification can influence the tribologic behavior of orthodontic materials even when the bulk properties of the wire remain unchanged.

Our finding that both bracket coating and wire coating independently reduced friction also agrees broadly with the direction of results reported by Hemanth et al. **[11]**, who found lower frictional resistance in nano-coated configurations than in conventional combinations. However, the literature is not uniform. Behroozian et al. **[12]** reported that coating porcelain brackets alone produced the lowest friction, whereas simultaneous coating of both the bracket and wire produced the highest friction in their experimental system. This contrasts with the present finding in which dual coating produced the lowest group means, particularly in artificial saliva. Differences in ceramic substrate, nanoparticle morphology, deposition protocol, coating thickness, ligation, and test design can substantially alter the final surface and may explain the divergent behavior.

The influence of the environment was also noteworthy. Artificial saliva reduced the pooled coefficient of friction from 0.31±0.09 to 0.26±0.08. This agrees with the general observation that the testing medium can modify bracket-wire friction, although the direction and magnitude of the effect depend on the materials being studied. Fidalgo et al. **[13]** demonstrated that bracket-wire combinations behave differently in artificial saliva, emphasizing the interaction between material type and oral simulation. The present data suggest that, for this ceramic bracket and epoxy-coated wire system, the mucin-based artificial saliva acted predominantly as a lubricant. This point is clinically relevant because dry bench testing may overestimate friction for some esthetic combinations.

Surface coating itself is also a critical determinant of performance. Farronato et al. **[14]** found that Teflon-coated orthodontic wires produced lower resistance to sliding than corresponding uncoated wires across several bracket-wire combinations. Conversely, esthetic coatings may degrade, roughen, or detach during use, and surface roughness varies considerably among commercially available esthetic archwires **[7]**. The favorable friction values obtained in the present study therefore reflect the immediate performance of newly prepared ZnO-coated specimens rather than long-term intraoral durability. Repeated sliding, thermal cycling, pH variation, dietary exposure, and tooth-brushing forces were not reproduced.

The present results also need to be interpreted in the broader context of nanoparticle coatings. Shah et al. **[15]** showed that a silver coating could either leave friction unchanged or reduce it depending on wire dimension, illustrating that the mechanical effect of a coating cannot be generalized solely from the coating material. Tanbakuchi et al. **[16]** similarly reported modestly lower friction after ZnO coating but no significant difference between two ZnO deposition methods. Therefore, the magnitude of benefit observed here should be considered specific to the dip-coating procedure, ceramic bracket type, epoxy archwire, and test parameters used in this thesis-derived experiment.

The clinical relevance of lowering friction lies in the possibility of reducing the force lost at the bracket-wire interface during sliding mechanics. Nevertheless, friction is only one component of resistance to sliding, and binding may become dominant once the wire contacts the bracket corners **[2]**, **[3]**. In addition, esthetic material selection is influenced by appearance as well as mechanics. Batista et al. **[6]** documented meaningful differences in the perceived attractiveness of different esthetic wires, while Chng et al. **[18]** showed that esthetic archwire materials may have distinct surface characteristics and wear behavior. Consequently, a clinically useful coating should preserve appearance, adhesion, biocompatibility, and durability in addition to lowering friction.

This study has several limitations. It was performed under controlled in vitro conditions and could not reproduce the full intraoral environment. Only one ceramic-bracket prescription, one epoxy-coated archwire dimension, one elastic ligation method, and one artificial-saliva formulation were evaluated. Coating thickness and post-test surface morphology were not quantified, and each specimen underwent only a single sliding event. These limitations restrict direct extrapolation to treatment duration or tooth-movement rate. Future work should incorporate surface characterization, repeated sliding cycles, thermal and chemical aging, multiple wire dimensions and ligation methods, and ultimately well-designed in vivo studies before routine clinical use is advocated.

CONCLUSION

Within the limitations of this in vitro study, ZnO nanoparticle coating significantly reduced the coefficient of friction of both ceramic brackets and epoxy esthetic archwires. The lowest friction was observed when both components were nano-coated and tested in artificial saliva, while the non-coated dry combination showed the greatest resistance. ZnO surface modification may therefore improve the sliding efficiency of esthetic orthodontic systems, but its durability and clinical effectiveness require further validation.

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