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Frictional resistance of low hysteresis superelastic orthodontic archwires after different metal oxide nanocoatings

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ABSTRACT

Aim: To compare the frictional resistance between uncoated and nanocoated low-hysteresis superelastic orthodontic archwires using three metal oxides: Aluminium oxide, titanium oxide, and zirconium oxide, when used with metal and ceramic orthodontic brackets.
Materials and Methods: A total of 120 segments of Low-hysteresis superelastic NiTi archwires (Tomy Orthodontics, Japan) measuring 25 mm, were divided into eight groups: uncoated, Al_2O_3-coated, TiO_2-coated, and ZrO_2-coated. Each group having 30 segments which were further divided into two subgroups of 15 each; for testing with metal and ceramic brackets. The nanocoatings were applied using a dip-coating method, followed by heat treatment to ensure adhesion. For frictional testing, upper premolar MBT prescription metal and ceramic brackets with 0.022-inch slots (Ormco, Brea, CA, USA) were mounted on a customised jig with a fixed interbracket distance. The archwires were tested individually by threading them through the brackets, and frictional resistance was measured using a universal testing machine at a sliding rate of 2 mm/min under dry conditions for a duration of one minute. Mean frictional values were recorded in N and then paired t test and ANOVA with Tukey's Post hoc LSD tests were done for comparison.
Results: The results showed that the uncoated wire with ceramic bracket showed the highest friction (21.9687 N) and the least friction was found with ZrO_2 coated wires with metal bracket (3.1253 N). Among the nanocoatings, the ZrO_2-coated wires demonstrated the lowest frictional resistance, followed by TiO_2 and Al_2O_3 coatings. Frictional resistance was significantly higher with ceramic brackets compared to metal brackets across all wire types, but the nanocoatings significantly reduced friction in both bracket types.
Conclusion: Metal oxide nanocoatings on low-hysteresis superelastic archwires significantly reduce frictional resistance, with zirconium oxide providing the most substantial reduction. These findings suggest that nanocoated wires, especially with ZrO_2, may enhance the efficiency of orthodontic treatments by minimizing frictional forces

1. Introduction

In modern orthodontics, archwires are the active component of fixed appliances commonly employed to close extraction spaces and align irregular teeth. During this technique, a portion of the applied force is used to overcome the system's inherent friction.[1] Understanding the frictional resistance between archwires and brackets is a critical factor which influences the efficiency of orthodontic treatment. It was observed that amount of friction in orthodontic appliances can impede the smooth movement of teeth as orthodontic tooth movement occurs only when the orthodontic forces can adequately overcome the frictional force between bracket and archwire.[2] Thus, increased friction prolongs treatment time and potentially causing patient discomfort.[3–5] Literature review shows that upto

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60% of the applied force is lost due to friction in sliding mechanics.[6]

In contemporary orthodontics, low-hysteresis superelastic archwires, such as Nickel-Titanium (NiTi) alloys, are widely utilized due to their ability to deliver consistent forces over a range of deflections, which helps maintain gentle, continuous tooth movement.[7–13] However, friction between archwires and brackets remains a challenge, particularly when ceramic brackets are used. Ceramic brackets, despite their aesthetic advantages, have been shown to produce higher frictional forces than metal brackets, primarily due to their rougher surface texture and higher rigidity.[14]

Efforts to reduce frictional resistance have led to various surface modifications of orthodontic archwires. One promising approach is nanocoating, where a thin layer of metal oxide nanoparticles is applied to the surface of the archwire, or brackets or both. Nanocoating on archwires enhances its surface properties by effectively decreasing its coefficients of friction, without compromising flexibility.[15–17] Along with modifying the surface properties, nanocoating has also been proven to incorporate antimicrobial properties to archwires and improve optical properties in aesthetic archwires.[18,19]

Studies have shown that metal oxide coatings, such as titanium oxide (TiO_2), zirconium oxide (ZrO_2), and Aluminium oxide (Al_2O_3), can improve surface smoothness and reduce frictional resistance in biomedical applications.[20,21] For instance, titanium oxide has been noted for its excellent biocompatibility and friction-reducing properties, making it a preferred choice in dental materials.[22] Zirconium oxide, meanwhile, is known for its high hardness and wear resistance, which could theoretically minimize friction in orthodontic applications.[23] Aluminium oxide nano coatings are considered highly biocompatible and also possess attractive optical properties like high transparency in the visible and ultraviolet light spectrum, making them suitable for various biomedical and optical applications along with reducing friction.[24,25]

Despite advancements, there remains limited data on the effects of metal oxide nanocoatings specifically on low-hysteresis superelastic archwires used with both metal and ceramic brackets. Existing studies have primarily focused on conventional NiTi wires or on coatings without specifying the frictional impact in aesthetic (ceramic) brackets. Given the growing preference for ceramic brackets among patients for aesthetic reasons, there is a pressing need to examine how nanocoated low-hysteresis wires interact with ceramic brackets, where friction is typically higher.

Therefore, the purpose of this study was to evaluate and compare the frictional resistance of uncoated and three metal oxide nanocoated low-hysteresis superelastic orthodontic archwires; specifically Aluminium oxide (Al_2O_3), titanium oxide (TiO_2), and zirconium oxide (ZrO_2); with both metal and ceramic brackets. By quantifying frictional resistance in these combinations, this study seeks to identify the most effective type of metal oxide coating for reducing friction and could contribute to more efficient treatment strategies and improved patient outcomes.

2. Materials and Methods

The study was done in Chennai, India in the year 2023 after obtaining Institutional board clearance. (SRMDC/IRB/2018/PhD/No.102)

120 archwire segments of equal dimensions (0.016 x .022 inches) and length 10cm were divided into eight groups (n=15). All the archwires were low hysteresis superelastic archwires (L&H Titan; Tomy Inc., Tokyo, Japan). Four groups were tested for friction with metal brackets and the other four with ceramic brackets. Upper premolar metal and ceramic brackets of .022 slot MBT prescription (Ormco, Brea, CA, USA) were used.

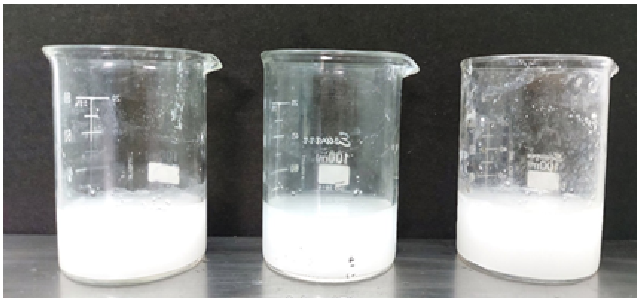

Figure 1: Three metal oxide nanoparticle solutions.

All the three nanoparticles (Al_2O_3, TiO_2 and ZrO_2) used for coating in the study were <50 nm in particle size. The nanocoating process was followed as given in a previous article by Dilip and Rajkumar in 2024.[26] The distal ends of the archwires were cut into 10 cm segments, washed thoroughly with ethanol under ultrasonication at 450HZ for 5 min. Nanoparticle suspensions of 10 mg/100ml of the three coating were prepared in 0.1% Chitosan and 1 mL glycerol with 10 mL isopropanol (Figure 1). The nanocoating was done using a combination of dip coating with ultra sonification followed by heat drying method (Figure 2). The wire segments were then inserted into the nanoparticle suspension and kept under ultra sonication for 10 cycles (Figures 3 and 4). This was followed by a process of drying in oven at 200°C for 1 hour. Samples from each group of archwire were verified using FESEM and SEM EDX for the nanocoating (Figures 5, 6 and 7).

The samples were divided into eight groups;

1. Group A - Uncoated archwires with metal brackets
2. Group B – Al_2O_3 nanocoated archwires with metal brackets

Figure 2: Archwire samples in the nanoparticle solution.

Figure 3: Archwire sample in ultrasonic device.

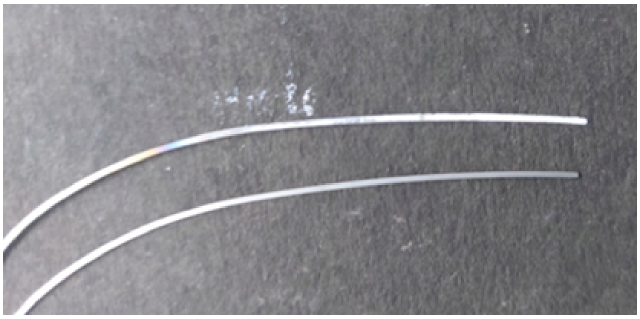

Figure 4: Uncoated and coated archwires.

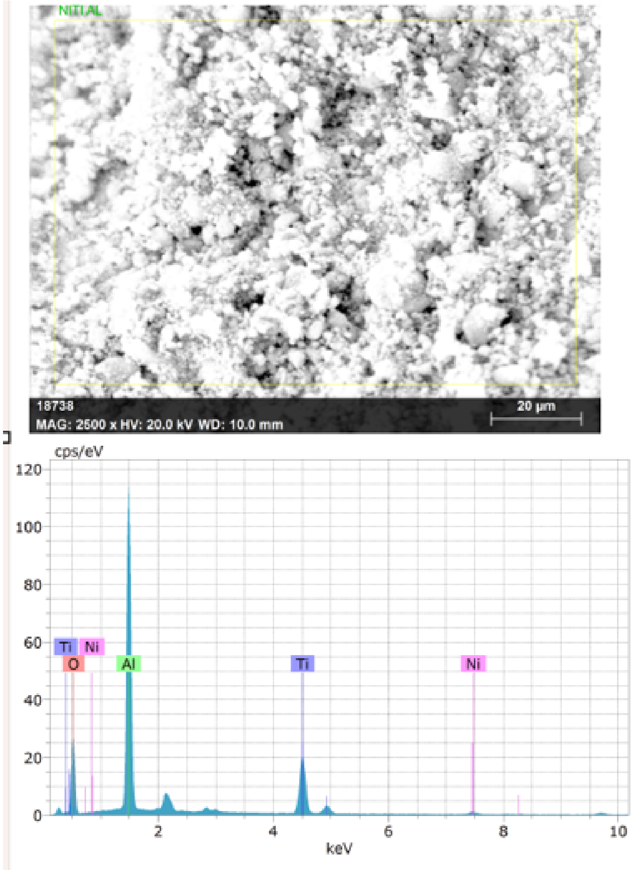

Figure 5: FESEM and Sem EDX of Al_2O_3 coated archwires

3. Group C – TiO_2 nanocoated archwires with metal brackets
4. Group D – ZrO_2 nanocoated archwires with metal brackets
5. Group E - Uncoated archwires with ceramic brackets
6. Group F – Al_2O_3 nanocoated archwires with ceramic brackets
7. Group G – TiO_2 nanocoated archwires with ceramic brackets
8. Group H – ZrO_2 nanocoated archwires with ceramic brackets

A customized jig was made consisting of five upper premolar metal brackets (Ormco, Brea, CA, USA) attached to an acrylic plate using cyanoacrylate glue (Figure 8). The distance between the brackets was 10 mm to mimic the inter-bracket distance. All the brackets were secured with 19 X 25 Stainless-steel archwires to maintain the alignment before attaching to the plate. The bracket in the centre alone was offset by 3 mm to simulate crowding in the arch. This jig was replicated for ceramic brackets also.

Prior to testing, the archwires were sterilised using isopropyl alcohol and dried with compressed air. The frictional properties of the archwires were measured using

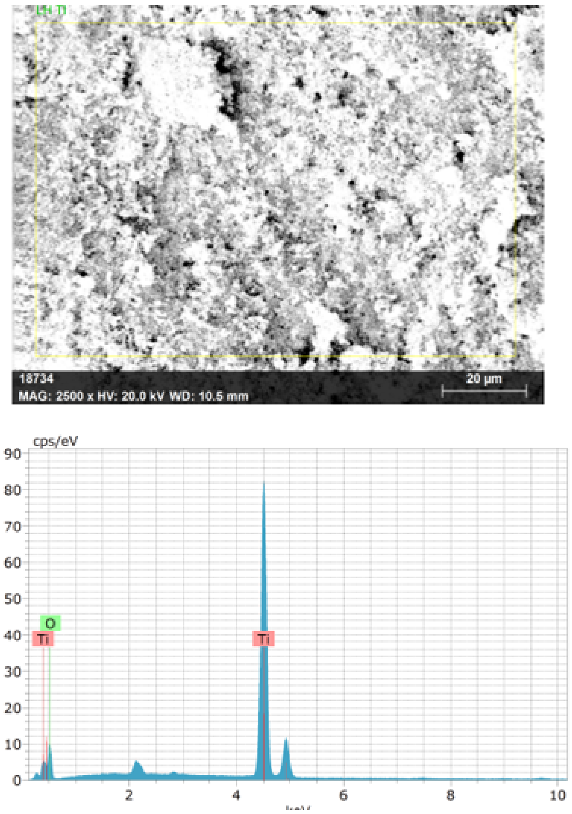

Figure 6: FESEM and sem EDX of TiO_2 coated archwires

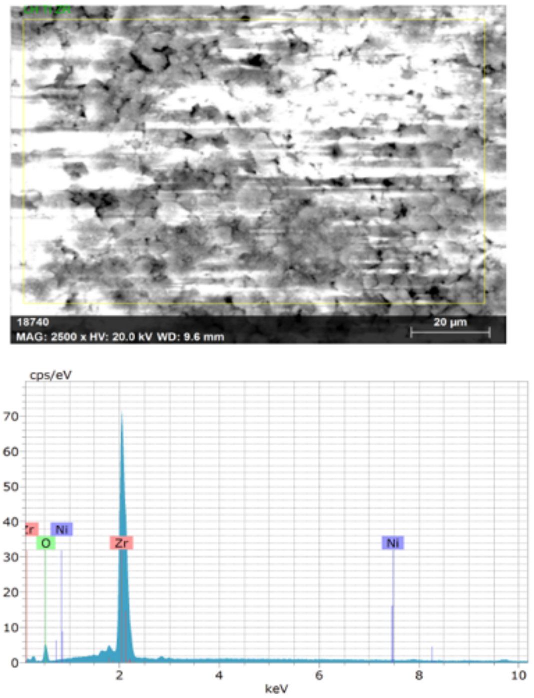

Figure 7: FESEM and sem EDX of ZrO_2 coated archwires

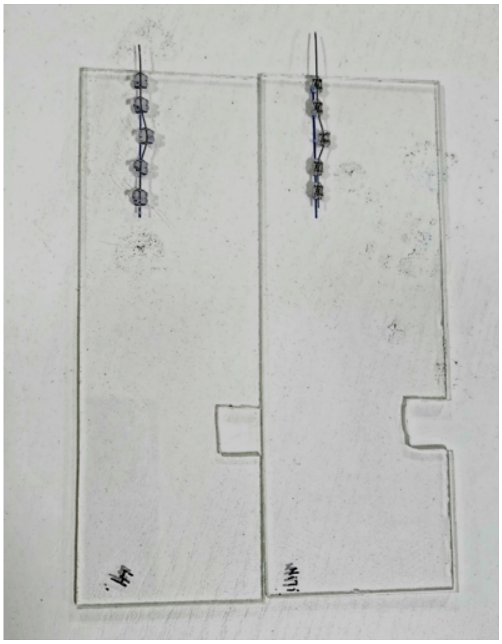

Figure 8: Customized jig for friction testing

the universal testing machine (Instron, Norwood, MA, USA). A 50g load was applied to each archwire and the frictional force was measured as the archwire was pulled through the brackets at the rate of 0.5 mm/min.

ANOVA followed by Tukey's LSD post-hoc test was performed using SPSS software, to compare the frictional resistance among the eight groups. An overall p-value of less than 0.05 was considered as statistically significant.

3. Results

The frictional behaviour of various metal oxide nanocoated wires and uncoated wires combined with metal and ceramic brackets revealed distinct patterns. Descriptive statistics are summarized in Table 1.

For metal brackets, the uncoated wires demonstrated a mean friction value of 5.87 ± 1.47 N, with a range of 2.91–7.71 N. The nano coated wires exhibited less frictional resistance compared to that of the control, uncoated wires. Among the nano coated wires, the Al_2O_3-coated wires exhibited higher friction with mean friction of 5.15 ± 1.33 N (range: 2.68–7.68 N). This was followed by TiO_2-coated wires, which had a comparable mean friction of 5.14 ± 1.99 N, but with a broader range (2.18–8.46 N), indicating greater variability. Notably, the ZrO_2-coated wires showed the lowest mean friction of 3.13 ± 0.46 N, with a narrow range (2.34–3.89 N), suggesting consistent friction performance in this bracket type.

Table 1: Descriptives

Friction								
		Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Uncoated wire in metal bracket	15	5.8743	1.47468	.38076	5.0577	6.6910	2.91	7.71
Al2O3 wire in metal bracket	15	5.1473	1.37272	.35444	4.3871	5.9075	2.66	7.66
TiO2 wire in metal bracket	15	5.1367	1.99256	.51448	4.0332	6.2401	2.18	8.46
ZrO22 wire in metal bracket	15	3.1253	.45822	.11831	2.8716	3.3791	2.34	3.89
Uncoated wire in ceramic bracket	15	21.9687	1.63538	.42225	21.0630	22.8743	18.96	25.51
Al2O3 wire in ceramic bracket	15	12.3509	1.77758	.45897	11.3665	13.3353	8.69	14.31
TiO2 wire in ceramic bracket	15	11.4227	2.11148	.54518	10.2534	12.5920	6.48	14.94
ZrO22 wire in ceramic bracket	15	11.1053	.74353	.19198	10.6936	11.5171	9.86	12.51
Total	120	9.5164	5.93500	.54179	8.4436	10.5892	2.18	25.51

Table 2: ANOVA

Friction					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3924.493	7	560.642	235.012	.000
Within Groups	267.186	112	2.386		
Total	4191.680	119			

Table 3: Multiple comparisons

Dependent Variable: Friction
LSD

• (I)	(J) Group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Uncoated wire in metal bracket	Al2O3 wire in metal bracket	.72700	.56398	.200	-.3905	1.8445
	TiO2 wire in metal bracket	.73767	.56398	.194	-.3798	1.8551
	ZrO2 wire in ceramic bracket	-5.23100*	.56398	.000	-6.3485	-4.1135
	ZrO2 wire in metal bracket	2.74900*	.56398	.000	1.6315	3.8665
	Al2O3 wire in ceramic bracket	-6.47653*	.56398	.000	-7.5940	-5.3591
	TiO2 wire in ceramic bracket	-5.54833*	.56398	.000	-6.6658	-4.4309
	Uncoated wire in ceramic bracket	-16.09433*	.56398	.000	-17.2118	-14.9769
Al2O3 wire in metal bracket	TiO2 wire in metal bracket	.01067	.56398	.985	-1.1068	1.1281
	ZrO2 wire in metal bracket	2.02200*	.56398	.001	.9045	3.1395
	Uncoated wire in ceramic bracket	-16.82133*	.56398	.000	-17.9388	-15.7039
	Al2O3 wire in ceramic bracket	-7.20353*	.56398	.000	-8.3210	-6.0861
	TiO2 wire in ceramic bracket	-6.27533*	.56398	.000	-7.3928	-5.1579
	ZrO2 wire in ceramic bracket	-5.95800*	.56398	.000	-7.0755	-4.8405
	Uncoated wire in metal bracket	-.72700	.56398	.200	-1.8445	.3905
TiO2 wire in metal bracket	ZrO2 wire in metal bracket	2.01133*	.56398	.001	.8939	3.1288
	Uncoated wire in ceramic bracket	-16.83200*	.56398	.000	-17.9495	-15.7145
	Al2O3 wire in ceramic bracket	-7.21420*	.56398	.000	-8.3317	-6.0967
	TiO2 wire in ceramic bracket	-6.28600*	.56398	.000	-7.4035	-5.1685
	ZrO2 wire in ceramic bracket	-5.96867*	.56398	.000	-7.0861	-4.8512
	Uncoated wire in metal bracket	-.73767	.56398	.194	-1.8551	.3798
	Al2O3 wire in metal bracket	-.01067	.56398	.985	-1.1281	1.1068
ZrO2 wire in metal bracket	Uncoated wire in ceramic bracket	-18.84333*	.56398	.000	-19.9608	-17.7259
	Al2O3 wire in ceramic bracket	-9.22553*	.56398	.000	-10.3430	-8.1081
	TiO2 wire in metal bracket	2.01133*	.56398	.001	.8939	3.1288
	ZrO2 wire in ceramic bracket	-7.98000*	.56398	.000	-9.0975	-6.8625
	Uncoated wire in metal bracket	-2.74900*	.56398	.000	-3.8665	-1.6315
	Al2O3 wire in metal bracket	-2.02200*	.56398	.001	-3.1395	-.9045
	TiO2 wire in ceramic bracket	-8.29733*	.56398	.000	-9.4148	-7.1799
Uncoated wire in ceramic bracket	Al2O3 wire in ceramic bracket	9.61780*	.56398	.000	8.5003	10.7353
	TiO2 wire in ceramic bracket	10.54600*	.56398	.000	9.4285	11.6635
	ZrO2 wire in ceramic bracket	10.86333*	.56398	.000	9.7459	11.9808
	Uncoated wire in metal bracket	16.09433*	.56398	.000	14.9769	17.2118
	Al2O3 wire in metal bracket	16.82133*	.56398	.000	15.7039	17.9388

Continued on next page

Table 3 continued

	TiO2 wire in metal bracket	16.83200*	.56398	.000	15.7145	17.9495
	ZrO2 wire in metal bracket	18.84333*	.56398	.000	17.7259	19.9608
	TiO2 wire in ceramic bracket	.92820	.56398	.103	-.1893	2.0457
	ZrO2 wire in ceramic bracket	1.24553*	.56398	.029	.1281	2.3630
Al2O3 wire in ceramic bracket	Uncoated wire in metal bracket	6.47653*	.56398	.000	5.3591	7.5940
	Al2O3 wire in metal bracket	7.20353*	.56398	.000	6.0861	8.3210
	TiO2 wire in metal bracket	7.21420*	.56398	.000	6.0967	8.3317
	ZrO2 wire in metal bracket	9.22553*	.56398	.000	8.1081	10.3430
	Uncoated wire in ceramic bracket	-9.61780*	.56398	.000	-10.7353	-8.5003
	ZrO2 wire in ceramic bracket	.31733	.56398	.575	-.8001	1.4348
TiO2 wire in ceramic bracket	Uncoated wire in metal bracket	5.54833*	.56398	.000	4.4309	6.6658
	Al2O3 wire in metal bracket	6.27533*	.56398	.000	5.1579	7.3928
	TiO2 wire in metal bracket	6.28600*	.56398	.000	5.1685	7.4035
	ZrO2 wire in metal bracket	8.29733*	.56398	.000	7.1799	9.4148
	Uncoated wire in ceramic bracket	-10.54600*	.56398	.000	-11.6635	-9.4285
	Al2O3 wire in ceramic bracket	-.92820	.56398	.103	-2.0457	.1893
ZrO2 wire in ceramic bracket	Uncoated wire in metal bracket	5.23100*	.56398	.000	4.1135	6.3485
	Al2O3 wire in metal bracket	5.95800*	.56398	.000	4.8405	7.0755
	TiO2 wire in metal bracket	5.96867*	.56398	.000	4.8512	7.0861
	ZrO2 wire in metal bracket	7.98000*	.56398	.000	6.8625	9.0975
	Uncoated wire in ceramic bracket	-10.86333*	.56398	.000	-11.9808	-9.7459
	Al2O3 wire in ceramic bracket	-1.24553*	.56398	.029	-2.3630	-.1281
	TiO2 wire in ceramic bracket	-.31733	.56398	.575	-1.4348	.8001

*. The mean difference is significant at the 0.05 level.

Ceramic brackets in general exhibited a higher frictional resistance as compared to that of metal brackets. The uncoated wires with ceramic brackets demonstrated the highest mean friction value of 21.99 ± 1.63 N, with a range of 18.08–25.61 N, significantly exceeding the friction of other wire types. Among the nano coated wires in ceramic brackets, which demonstrated less friction as compared to that of control, the Al_2O_3-coated wires showed a mean friction of 12.35 ± 1.78 N (range: 8.89–14.31 N), followed closely by the TiO_2-coated wires with a mean friction of 11.43 ± 2.11 N (range: 6.86–14.94 N). The ZrO_2-coated wires in ceramic brackets exhibited the lowest mean friction of 11.11 ± 7.74 N which is comparable to TiO_2 however, the larger standard deviation reflects substantial variability, with friction ranging from 9.86–12.51 N.

When analysed collectively, the overall mean friction across all groups was 9.62 ± 5.94, with values spanning a wide range from 2.18 to 25.61. The confidence intervals for each wire-bracket combination indicate minimal overlap, suggesting that the frictional performance of different combinations is statistically distinct.

These results highlight the significant influence of both wire coating and bracket material on friction. Uncoated wires consistently exhibit higher friction, particularly in ceramic brackets, whereas ZrO_2-coated wires offer the lowest and most consistent friction, especially in metal brackets.

A one-way ANOVA was conducted to compare the frictional forces among different wire and bracket combinations. The results revealed a statistically significant difference in mean friction values across the groups ($p < 0.001$). (Table 2)

Post hoc comparisons using the LSD test revealed significant differences in friction between wire and bracket combinations. (Table 3)

The uncoated wire in ceramic brackets exhibited the highest friction, significantly exceeding all other groups ($p < 0.001$). In contrast, the ZrO_2-coated wire in metal brackets consistently showed the lowest friction, with significant differences compared to all ceramic bracket groups ($p < 0.001$).

The friction exhibited by uncoated wires with metal brackets didn't have significant difference when compared to the friction exhibited by Al_2O_3 wires and TiO_2 wires on metal brackets. (p=.200, p=.194). Also, the friction with Al_2O_3 wires on metal brackets and TiO_2 wires on metal brackets were comparable and not statistically different (p=.985). However, the ZrO_2-coated wire in metal brackets showed significantly lower friction compared to all other metal bracket combinations. ($p < 0.001$)

Among ceramic brackets, wires coated with Al_2O_3 and TiO_2 demonstrated moderately high friction, with no significant difference between these two coatings ($p = 0.103$). However, the difference in friction between ZrO_2-coated wires and TiO_2 coated wires in ceramic brackets was not statistically significant. (p=.575)

These findings highlight the substantial influence of both wire coating and bracket material on friction, with ZrO_2 coatings and metal brackets consistently showing reduced frictional forces.

4. Discussion

Frictional force plays a critical role in orthodontic sliding mechanics, as it reduces the effective force applied to achieve tooth movement, thereby increasing treatment time and posing additional challenges. Lowering friction allows orthodontists to use lighter forces, which offers significant benefits, such as reduced risk of root resorption, better anchorage control, minimized patient discomfort, and shorter treatment durations. To address this issue, orthodontic research has increasingly turned to material engineering, with nanotechnology emerging as a highly effective solution. Coating orthodontic archwires with nanoparticles has been particularly promising. These coatings create smoother surfaces on the wires, significantly reducing frictional resistance between the wires and brackets. Metal oxide nanoparticles, for instance, improve the mechanical properties and surface smoothness of archwires without compromising flexibility or biocompatibility. This innovation enables more efficient tooth movement and better overall treatment outcomes. By integrating nanoparticle-coated wires into orthodontic care, practitioners can achieve enhanced performance and provide patients with a more effective and comfortable treatment experience.

This study assessed the impact of three metal oxide nanocoatings—aluminium oxide (Al_2O_3), titanium oxide (TiO_2), and zirconium oxide (ZrO_2)—on the frictional resistance of low-hysteresis superelastic orthodontic archwires with metal and ceramic brackets. The findings suggest that nanocoated wires exhibit reduced frictional resistance compared to uncoated wires in both types of brackets, with zirconium oxide consistently showing the greatest reduction in frictional force. These results have several implications for clinical orthodontic practice and confirm previous literature suggesting that surface modifications can enhance the mechanical properties of orthodontic materials.

The frictional resistance observed in ceramic brackets was generally higher than in metal brackets, consistent with prior studies that indicate ceramic's inherently rougher texture and increased hardness contribute to greater friction with archwires.[14–22] However, all three nanocoatings effectively reduced friction in ceramic brackets with ZrO_2 nanocoating showing the most significant reduction.

The efficiency of ZrO_2 in reducing the friction aligns with study done by Park and Lim (2017), which highlighted ZrO_2's superior wear resistance and smooth surface finish as factors that minimize friction in orthodontic applications.[23] The improved performance of ZrO_2 coatings may be attributed to the hardness and durability of zirconium oxide, which likely contributes to a smoother surface interaction and thus a lower coefficient of friction between the archwire and bracket. In a study by Golshah et al. (2022), ZrO_2 nanocoating significantly reduced friction for TMA wires whereas stainless steel and NiTi wires showed reduced friction as compared to uncoated wires but is not statisfically significant.[27]

In comparison, TiO_2-coated wires also showed a significant reduction in frictional resistance, though not as substantial as ZrO_2. Titanium oxide has been previously noted for its biocompatibility and ability to lower friction due to its favourable surface characteristics, as demonstrated in studies by Lee et al. (2015), Hemanth et al. (2023), and Dilip et al. (2023).[15,20,26] However, its relatively lower hardness compared to zirconium oxide may account for the smaller reduction in frictional force, particularly in ceramic brackets where surface roughness and hardness play a critical role in frictional behaviour.[27]

Al_2O_3, while effective, showed the least reduction in friction among the three nanocoatings, possibly due to its comparatively lower wear resistance, which may result in a less durable coating over repeated bracket-wire interactions. This is in accordance with a study done by Palanivel et al. (2022), where Al_2O_3 nanocoating had a reduction in friction but is not as effective as Zinc oxide nanocoating.[25] However, in a study done by Arici in 2021, they demonstrated a statistically significant decrease in the coefficient of friction in archwires with metal brackets using Al_2O_3 nanocoating.[28]

The observed reduction in frictional resistance with nanocoated wires has clinical implications, particularly for patients who opt for ceramic brackets. Reducing friction in ceramic brackets, which tend to hinder smooth tooth movement due to higher friction, could lead to more efficient treatment progress and a potentially shorter treatment duration. Moreover, the reduced frictional forces with nanocoated wires could lessen the overall force required to move teeth, thereby minimizing patient discomfort and the risk of root resorption associated with high-force applications.[3]

This study was conducted in an in vitro setting, which may not entirely replicate the complex conditions in an oral environment, such as temperature fluctuations and the presence of saliva. Future studies should explore in vivo testing of nanocoated archwires to confirm these findings under real clinical conditions. Additionally, examining the long-term durability of these nanocoatings and their resistance to degradation over time could provide insights into the longevity of their friction-reducing effects. Further research into alternative nanocoating materials or combinations of metal oxides may also yield coatings that provide even more optimal results for reducing friction in orthodontic applications.

In conclusion, this study supports the potential of metal oxide nanocoatings, particularly zirconium oxide, in reducing frictional resistance in orthodontic archwires used with both metal and ceramic brackets. Implementing such surface modifications could enhance treatment efficiency, improve patient comfort, and support the growing demand for aesthetic orthodontic solutions.

5. Conclusion

The study showed that all three coatings significantly lower friction compared to uncoated wires, with zirconium oxide proving to be the most effective, followed by titanium oxide and aluminium oxide. While ceramic brackets exhibited higher frictional resistance overall, nanocoating substantially mitigated this challenge, particularly with ZrO_2-coated wires. These results underscore the potential of nanocoated wires to enhance orthodontic treatment efficiency by minimizing friction, thereby enabling smoother tooth movement, reducing overall treatment time, and improving patient comfort.

6. Source of Funding

None.

7. Conflict of Interest

None.

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