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Comparative Analysis of Frictional Resistance and Deflective Force in Aluminium Oxide Nanocoated Superelastic Orthodontic Archwires: An In Vitro Study

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Abstract

To evaluate and compare the frictional resistance and deflective force between three types of superelastic orthodontic archwires with and without nanocoating with Aluminium oxide (Al_2O_3) nanoparticles with both metal and ceramic brackets. A total of 90 samples were divided into two groups with 45 in uncoated category and 45in coated with Al_2O_3 nanoparticles category. Under both categories there were 15 wire segments consisting of three types of orthodontic archwires, namely; Low hysteresis superelastic archwire (L&H Titan; Tomy Inc., Tokyo, Japan), Nickel-titanium (NiTi) archwires (Ormco, Brea, CA, USA) and CuNiTi archwires (Ormco, Brea, CA, USA). All the wires were of equal dimensions (0.016 x .022 inches) and length (10 cm). The frictional properties of the archwires were measured using a universal testing machine (Instron, Norwood, MA, USA) mounted on a custom-made jig. Both metal and ceramic brackets (Ormco, Brea, CA, USA) were used to analyse the friction for each type of archwire. The deflective force at 4mm was also evaluated for the six groups. The data were analysed using independent Student t-tests to compare the mean frictional resistance of the three archwires followed by analysis of variance (ANOVA) to evaluate differences between the means with p-value of less than 0.05 considered as statistically significant. The results of this study showed that all three types of archwires had significantly lower friction with the metal brackets compared to the ceramic brackets. The low hysteresis archwires had the least friction both in the uncoated and nanocoated categories compared to the other two archwires. The results of the study also indicate that there was a significant reduction in frictional resistance in the Al_2O_3 nanocoated archwires compared to their uncoated counterparts. Additionally, the difference between the deflective force with and without nanocoating was not statistically significant. Low hysteresis archwires produced the least friction compared to Niti and CuNiTi archwires. Archwires coated with Al_2O_3 nanoparticles showed significantly reduced frictional resistance and that the deflective force remains unchanged after nanocoating with Al_2O_3.

Keywords: Nanocoating, Superelastic Archwires, Low Hysteresis, Aluminium Oxide Nanoparticles.

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1. Introduction

Frictional resistance between orthodontic archwires and brackets is a crucial factor affecting treatment efficiency. Excessive friction can impede tooth movement, leading to prolonged treatment durations and increased patient discomfort. Superelastic archwires, known for their ability to deliver consistent forces during tooth movement, have gained popularity in orthodontic practice. The result of a study by Angolkar et al, showed that the frictional forces produced by the wires of four alloys in ceramic and stainless-steel brackets. It was suggested that, for most sizes, the wires in ceramic brackets produced significantly greater friction [1]. This difference may be attributed to some characteristic of the bracket material or slot surface texture. Orthodontic treatment has undergone significant advancements in materials and techniques to achieve more efficient and patient-friendly outcomes. The focus on reducing frictional resistance without compromising the mechanical properties has driven researchers to explore innovative materials and coatings. One such area of interest is the application of nanotechnology to orthodontic archwires. Studies have been conducted utilising the antimicrobial property of nanoparticles on orthodontic archwires [2]. These nanoparticles also help in improving the mechanical properties of the orthodontic appliances. One such is Aluminium oxide and is emerging as a promising nanocoating due to its biocompatibility and hardness.

It presents a promising solution for enhancing the surface properties of orthodontic archwires. The application of nanocoating aims to create a smoother and more lubricious surface, potentially reducing frictional resistance and improving the predictability of deflective forces during tooth movement. Many previous studies have only tested the properties of NiTi and CuNiTi archwires and very few studies about the Low hysteresis NiTi archwires [3]. Studies by Kapila et al, Stannard et al and Philippa Rudge et al, had concluded that friction is highest with superelastic NiTi archwires compared to stainless steel, and Elgiloy archwires [4-6]. Some studies have tried nanocoating of stainless steel archwires with reduction in frictional properties [7-8]. But there is currently a lack of evidence on the effect of nanocoating of superelastic archwires, especially low hysteresis archwires on the frictional resistance and deflective force. These Low hysteresis archwires are of importance as they have been shown to deliver more stable orthodontic forces [9]. The deflective property of the archwire determines the type of force to be exerted. Orthodontic wires for levelling and alignment must be able to exert light and continuous forces and thus transmit them in a wide range of activation. Therefore, the purpose of this in vitro study was to evaluate and compare the frictional resistance and deflective force between three types of superelastic orthodontic archwires with and without nanocoating with Aluminium oxide nanoparticles with both metal and ceramic brackets. By employing a custom-designed mechanical testing apparatus, this research aims to contribute valuable insights into the potential benefits of nanocoating in enhancing orthodontic superelastic archwire performance.

2. Materials and methods

A total of 90 samples were divided into two groups with 45 in uncoated category and 45 in coated with Aluminium oxide nanoparticles category. 15 were allotted in each category respectively from low hysteresis superelastic archwires (L&H Titan; Tomy Inc., Tokyo, Japan), NiTi archwires (Ormco, Brea, CA, USA) and NiTi with copper (CuNiTi) archwires (Ormco, Brea, CA, USA) of equal dimensions (0.016 x .022 inches) and length (10cm). They were randomly assigned in combination among metal and ceramic orthodontic bracketsgroup. Upper first premolar brackets (Ormco, Brea, CA, USA) were used.Among 15 samples, ten were allotted between metal and ceramic orthodontic brackets groups of five each while the remaining five samples were used for assessing deflective force at 4 mm. The Al_2O_3nanoparticles (<50 nm particle size (DLS), 20 wt. % in isopropanol) was used for coating in the study (Figure 1). The distal ends of the archwires were cut into 6 cm segments, washed thoroughly with ethanol under ultrasonication at 450HZ for 5 min. An Al_2O_3nanoparticle suspension of 10 mg/100ml was prepared in 0.1% Chitosan and 1 mL glycerol with 10 mL isopropanol. The wire segments were then inserted into the nanoparticle suspension and kept under ultra sonication for 10 cycles (Figure 2). This was followed by a process of drying in oven at 200˚C for 1 hour (Figure 3). In this study, three types of superelastic archwires namely; NiTi, CuNiTi and Low hysteresis NiTi archwires (Figure 4), with and without nanocoating with aluminium oxide nanocoating, were tested for frictional resistance with both metal and ceramic brackets. Therefore, there were 12 groups in total (figure 5 & 6). The frictional resistance between archwires and brackets was assessed using the testing apparatus, which replicated the dynamic conditions of the oral cavity. A customised jig was made consisting of five brackets attached to an acrylic plate using cyanoacrylate glue. 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. Prior to testing, the archwires were sterilised using isopropyl alcohol and dried with compressed air. The frictional properties of the archwires were measured using the universal testing machine (Instron, Norwood, MA, USA) mounted on a custom-made jig. The jig consisted of five brackets with the archwire passing through the brackets and secured by ligature wire (Figures 7 & 8). 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 0.5mm/min [10-11]. Institutional ethical clearance was obtained (SRMDC/IRB/2018/PhD/No.102). The deflective force at 4 mm was also measured using the universal testing machine. The archwire was secured in the machine's grips, and a tensile load was applied at a rate of 1mm/min until the wire was deflected up to 4 mm. The force was then recorded. Independent Student t-tests were used to compare the mean frictional resistance between metal and ceramic orthodontic brackets group. Kruskal Wallis test followed by Dunns post-hoc test was performed to compare the frictional resistance between the three archwire categories while one-way ANOVA and Tukey's honest significant difference (HSD) was done to evaluate the differences in the tensile strength, compressive strength and deflective force between the archwires with an overall p-value of less than 0.05 considered as statistically significant.

3. Results

The results of the frictional resistance is shown in Table 1 and 2. Among the uncoated archwire, Low hysteresis NiTi archwires showed lower friction with metal brackets (4.0200$\pm$ .31937 N) followed by Copper NiTi (7.2400$\pm$ 1.87297) and NiTi (7.4800 $\pm$ 1.72105 N). With ceramic brackets, Low hysteresis NiTi archwires showed lower friction (13.6800 $\pm$ .95237 N) followed by CuNiTi (14.2000$\pm$ .94340 N) and NiTi (19.6200 $\pm$ 1.83085 N). Among the coated archwire, Low hysteresis NiTi archwires showed lower friction with metal brackets (1.0000 $\pm$ .55678 N) followed by NiTi (3.3200 $\pm$ .82885 N) and CuNiTi (4.5200 $\pm$ 1.82401 N). With ceramic brackets, Low hysteresis NiTi archwires showed lower friction (4.1000 $\pm$ .79687 N) followed by CuNiTi (7.1200 $\pm$ 1.44465 N) and NiTi (7.4800 $\pm$ 1.65439 N)**.** Metal brackets showed lower friction irrespective of the type of archwire used. And the Al_2O3 coated archwires showed lower friction in all three archwires irrespective of the type of bracket used. Friction between Low hysteresis NiTi archwires coated with Al_2O3 and the metal brackets recorded the least friction (1.0000 $\pm$ .55678 N). Friction between uncoated NiTi and ceramic bracket recorded the highest friction (19.6200 $\pm$ 1.83085 N). The results of the deflective force at 4 mm is given in Table 3 and 4. The results of the deflective force at 4 mm for the uncoated category showed that the lowest force was produced by Low hysteresis archwires (metal - 234.40 $\pm$ 7.893 N, ceramic – 235.00 $\pm$ 8.944 N) followed by CuNiTi wires (metal - 253.60 $\pm$ 7.232 N, ceramic – 260.40 $\pm$ 8.820 N) and the highest force by the NiTi wires (metal - 276.60 $\pm$ 19.995 N, ceramic – 278.80 $\pm$ 18.512 N). The deflective at 4 mm for the coated category showed similar results with the lowest force produced by low hysteresis wires (metal – 229.40 $\pm$ 5.030 N, ceramic- 226.80 $\pm$ 5.167 N) and highest by NiTi wires (metal – 276.60 $\pm$ 27.835 N, ceramic – 274.00 $\pm$ 21.319 N). The comparison between coated and uncoated wires between each of the three types of superelastic archwires was not statistically significant. This showed that the deflective force after nanocoating remained the same for all the three types of archwires. To summarize, the low hysteresis archwires had the least friction both in the uncoated and nanocoated categories compared to the other two archwires. The results of the study also indicate that there was a significant reduction in frictional resistance in the aluminium oxide nanocoated archwires compared to their uncoated counterparts in all the three types of archwires. Additionally, the difference between the deflective force with and without nanocoating was not statistically significant.

4. Discussion

Orthodontic archwires play a pivotal role in the biomechanics of tooth movement. Superelastic archwires are widely used in clinical orthodontics because it has excellent elasticity that maintains the load-deflection curve. Usually, this kind of wire demonstrates elasticity by changing its crystal structure from austenitic to martensitic phase when altered by force. The quest for improved archwire materials has led to the exploration of new technology in metallurgy to enhance their properties. One such innovation is the development of the Low Hysteresis superelastic archwire by Tomy Orthodontics, Japan [12]. Low hysteresis archwires are supposed to exhibit minimal energy loss during loading and unloading cycles. This characteristic allows for more efficient force delivery to the teeth, ensuring that the applied forces are maintained over time. This efficiency is crucial for achieving predictable tooth movement and optimizing treatment outcomes. The application of low hysteresis archwires can lead to reduced forces required for tooth movement. Lower forces contribute to decreased discomfort and pain for patients during orthodontic treatment. The manufacturers claim that these low hysteresis wires compared to pre-existing Ni-Ti wires, have a 17% narrower range of load change when intra-oral temperature changes. Therefore, it is possible to keep the orthodontic force to a constant level during active treatment. Reduced frictional resistance holds significant clinical implications. Orthodontic treatments often encounter challenges associated with friction-induced discomfort, prolonged treatment durations, and unpredictable tooth movement. Previous studies have shown high frictional resistance with all superelastic archwires [4-6]. The quest for improved archwire materials has led to the exploration of nanotechnology to enhance their properties. Aluminium oxide nanoparticles, known for its biocompatibility and hardness, are ideal as a coating in this regard [13]. The present in vitro study delves into the intriguing realm of orthodontic materials, specifically exploring the impact of aluminium oxide nanocoating on frictional resistance and deflective force in superelastic orthodontic archwires. The improved surface properties may reduce the binding effects between the archwire and the bracket, thereby facilitating more efficient tooth movement. The findings will shed light on the potential of nanotechnology to refine orthodontic treatment dynamics, offering a glimpse into the future of improved biomechanics and patient outcomes. The highest frictional resistance was found with uncoated NiTi archwires when used with ceramic brackets (19.6200 $\pm$ 1.83085 N). Low hysteresis NiTi archwires coated with Al_2O3 and the metal brackets recorded the least frictional resistance (1.0000 $\pm$ .55678 N). Ceramic brackets consistently showed higher friction compared to metal brackets regardless of the type of archwire used and this was statistically significant. This was in accordance with previous studies by Angolkar et al, Pratten et al and Nishio et al [1,14-15]. Low hysteresis archwires showed reduced frictional resistance compared to the other two archwires and this was found to be statistically significant. This reiterates the conclusions of the study done by Liaw YC et al and Dilip et al [12,3]. The probable reason for the reduced frictional behaviour maybe the increased flexibility and low load\ deflection rate which decrease the edge binding of the archwire to the bracket. Nanocoating of the archwires reduced the frictional resistance with respect to all archwires and they were statistically significant. This shows that Al_2O_3 has the potential to alter the surface properties favourably. Previous studies by Arici et al showed similar results but they had used stainless steel archwires in their study [16]. Deflective force, a critical factor in orthodontic treatment planning, was measured systematically to evaluate the impact of nanocoating on force delivery. The results of this study indicated that the lowest force was produced by the low hysteresis archwires (uncoated archwire with metal bracket - 234.40 $\pm$ 7.893 N, ceramic – 235.00 $\pm$ 8.944 N, coated archwire with metal bracket – 229.40 $\pm$ 5.030 N, ceramic- 226.80 $\pm$ 5.167 N) and the values were statistically significant. This was probably because of the low load deflection rate due to the special heat treatment carried out during the manufacturing process. CuNiTi had lesser force levels (uncoated archwire with metal bracket - 253.60 $\pm$ 7.232 N, ceramic – 260.40 $\pm$ 8.820 N, coated archwire with metal bracket – 254.60 $\pm$ 8.849 N, ceramic – 247.20 $\pm$ 12.988 N) than Niti wires (uncoated archwire with metal bracket - 276.60 $\pm$ 19.995 N, ceramic – 278.80 $\pm$ 18.512 N, coated archwire with metal bracket – 276.60 $\pm$ 27.835 N, ceramic – 274.00 $\pm$ 21.319N) but higher than the low hysteresis archwires. This was in accordance with the study done by Liaw YC et al [12]. The nanocoated archwires showed a similar pattern of deflective force, suggesting no significant effect on the mechanical properties due to the coating process or the coating per se. This finding has important clinical implications, as deflective force is the major advantage of superelastic archwires and any attempt to reduce friction should not be at the cost of compromising the mechanical properties of these wires. Orthodontic treatments often rely on precise control of force application to achieve predictable tooth movement. The results of the study show that nanocoating has no deleterious effect on the mechanical property of the archwires but significantly reduced the frictional characteristics. The promising results from this in vitro study lay the groundwork for potential advancements in orthodontic treatment protocols. The reduced frictional resistance observed in aluminium oxide nanocoated archwires suggest that nanocoating holds promise for enhancing the performance of superelastic orthodontic archwires. While this in vitro study provides valuable insights, further research is necessary to validate these findings in clinical settings. Further clinical trials are needed to assess the implications of aluminium oxide nanocoating on treatment outcomes, including patient discomfort, treatment duration, and the tenacity of the coating. Long-term biocompatibility, durability of the coating, and the cost-effectiveness of the process are factors that merit careful scrutiny.

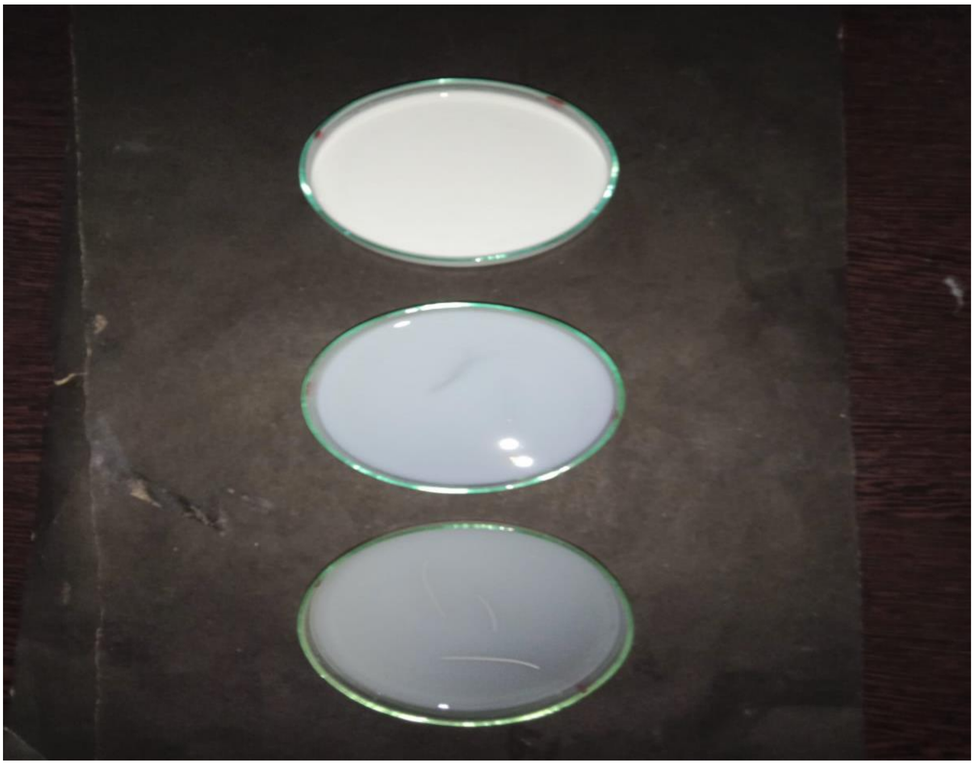


Figure 1: Nanoparticle suspension prepared for the three types of archwires.

Figure 2: Ultra sonification.

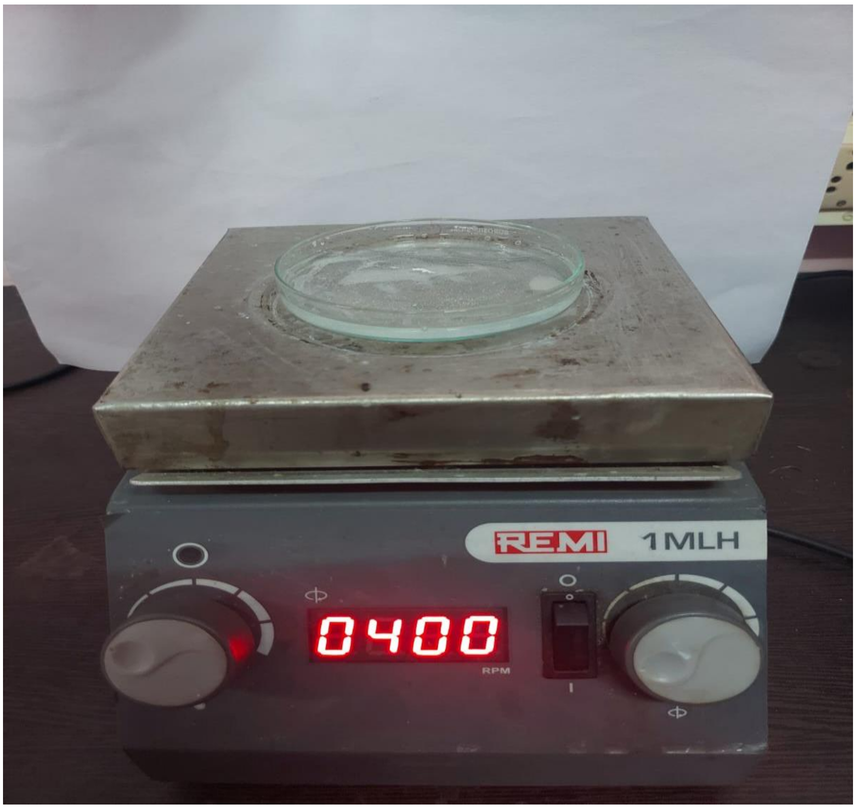


Figure 3: Drying in hotplate at 400º F (200 ºC).

Figure 4: Low hysteresis superelastic archwires – left (L&H Titan; Tomy Inc., Tokyo, Japan), NiTi archwires –right (Ormco, Brea, CA, USA) and NiTi with copper (CuNiTi) archwires – middle (Ormco, Brea, CA, USA).

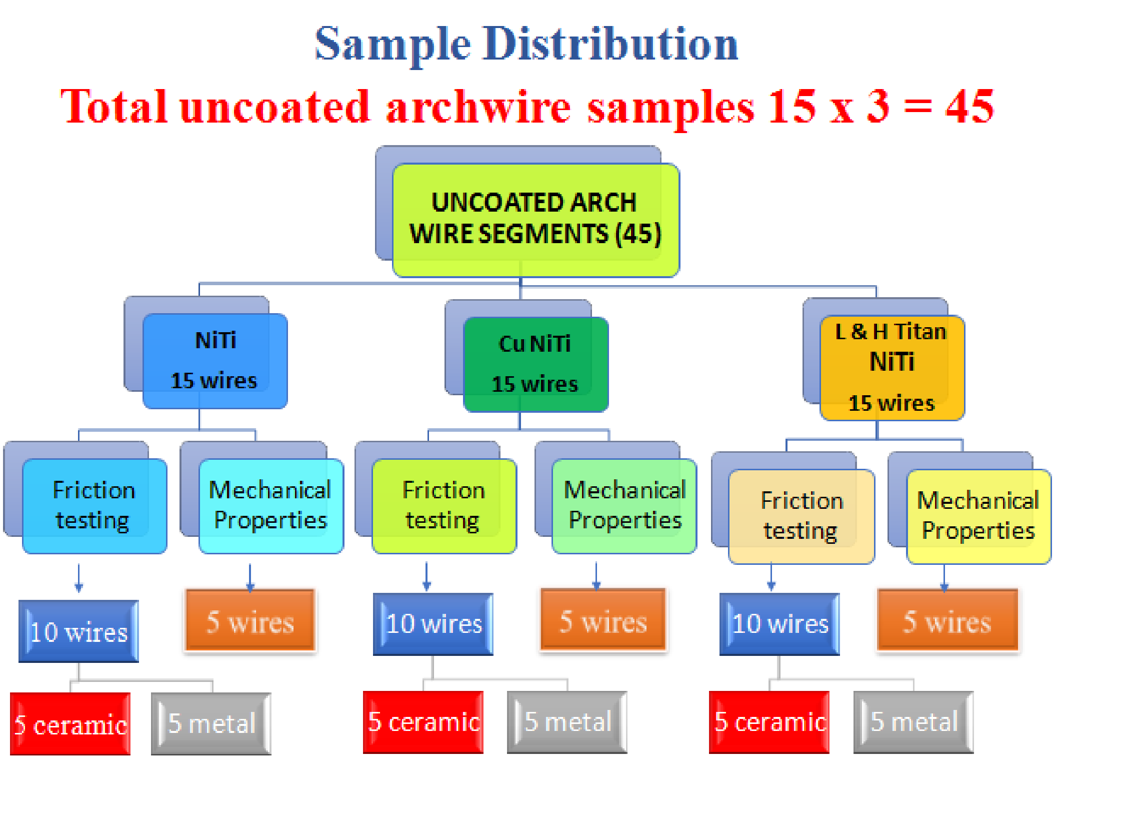


Figure 5: Sample distribution of uncoated archwire samples.

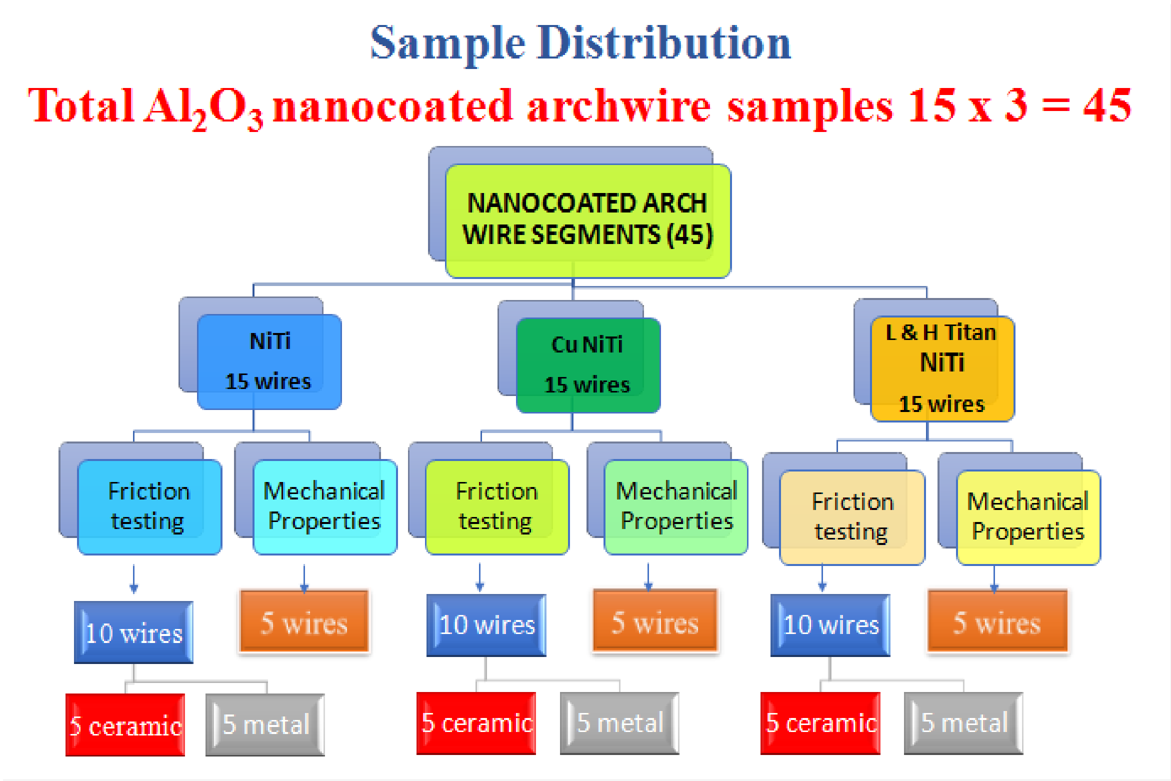


Figure 6: Sample distribution of Al_2O_3 coated archwire samples.

Figure 7: Customized Zig for friction evaluation.

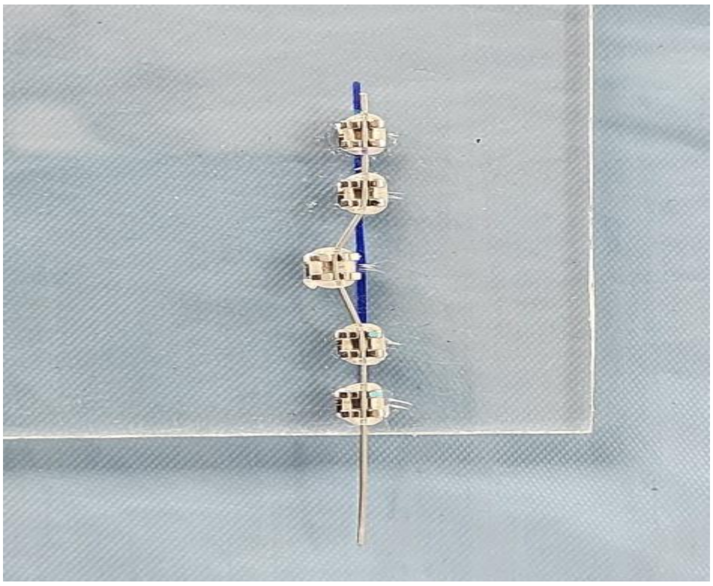


Figure 8: The bracket in the centre alone was offset by 3 mm to simulate crowding in the arch.

Table 3: Descriptive analysis of the Deflective force at 4 mm, in the 6 groups

Wire and bracket combination	N	Mean	Std. Dev	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
NiTi	5	276.60	19.995	8.942	251.77	301.43	254	296
CuNiTi	5	253.60	7.232	3.234	244.62	262.58	243	260
L & H Titan NiTi	5	234.40	7.893	3.530	224.60	244.20	224	245
NiTi coated with (Al_2O_3)	5	274.00	21.319	9.534	247.53	300.47	254	304
CuNiTi coated with (Al_2O_3)	5	247.20	12.988	5.809	231.07	263.33	227	260
L & H Titan NiTi coated with (Al_2O_3)	5	226.80	5.167	2.311	220.38	233.22	221	234
Total	30	253.95	23.012	2.971	248.01	259.89	221	316

Table 1: Descriptive analysis of the Friction Resistance in the 12 groups

Wire and bracket combination		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Min	Max	Between-Component Variance
NiTi with Metal		5	7.4800	1.72105	.76968	5.3430	9.6170	5.30	9.90	
CuNiTi with Metal		5	7.2400	1.87297	.83762	4.9144	9.5656	4.90	10.10	
L & H Titan NiTi with Metal		5	4.0200	.31937	.14283	3.6234	4.4166	3.60	4.40	
NiTi with Ceramic		5	19.6200	1.83085	.81878	17.3467	21.8933	17.20	21.50	
CuNiTi with Ceramic		5	14.2000	.94340	.42190	13.0286	15.3714	12.90	15.10	
L & H Titan NiTi with Ceramic		5	13.6800	.95237	.42591	12.4975	14.8625	12.40	14.90	
NiTi (Al_2O_3) with Metal		5	3.3200	.82885	.37068	2.2908	4.3492	2.30	4.30	
CuNiTi (Al_2O_3) with Metal		5	4.5200	1.82401	.81572	2.2552	6.7848	2.20	6.10	
L & H Titan NiTi (Al_2O_3) with Metal		5	1.0000	.55678	.24900	.3087	1.6913	.30	1.70	
NiTi (Al_2O_3) with Ceramic		5	7.4800	1.65439	.73986	5.4258	9.5342	5.30	9.20	
CuNiTi (Al_2O_3) with Ceramic		5	7.1200	1.44465	.64607	5.3262	8.9138	5.20	8.80	
L & H Titan NiTi (Al_2O_3) with Ceramic		5	4.1000	.79687	.35637	3.1106	5.0894	3.20	5.30	
Total		60	7.8150	5.35578	.69143	6.4315	9.1985	.30	21.50	
Model	Fixed Effects			1.33866	.17282	7.4675	8.1625			
	Random Effects				1.56009	4.3813	11.2487			28.84815

Table 2: Mean Plot for Frictional resistance in the 12 groups

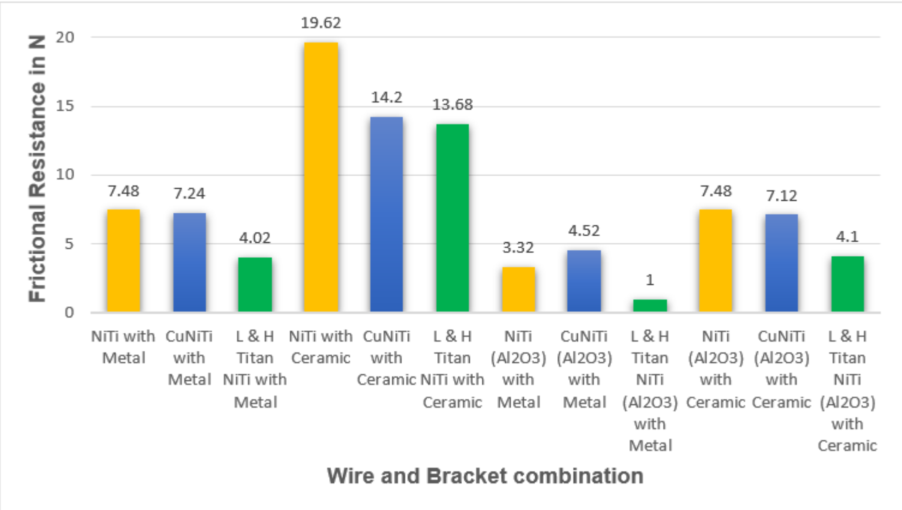
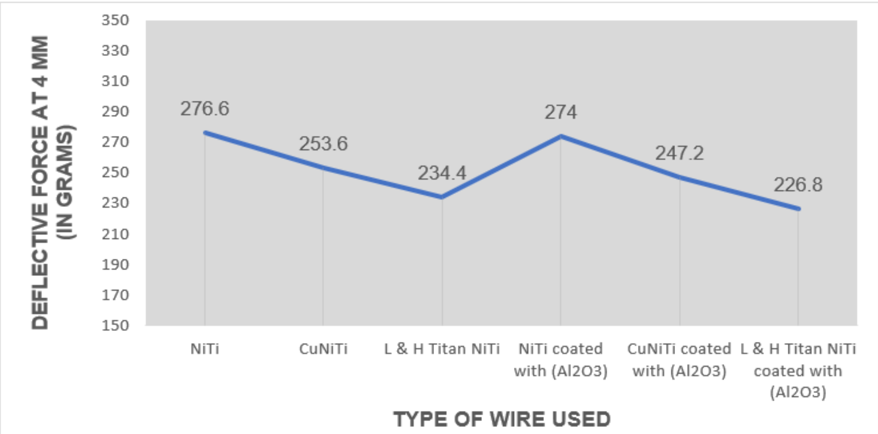


Table 4: Mean plot of the Deflective force at 4 mm, in the 6 groups



4. Conclusions

The conclusions of the study were

1. Low hysteresis archwires produced the least friction compared to Niti and CuNiTi archwires.
2. Metal brackets had lower friction compared to ceramic brackets with all archwires.
3. Archwires coated with Al_2O_3 nanoparticles showed significantly reduced frictional resistance.
4. The lowest deflective forces were produced by the low hysteresis wires followed by the CuNiTi and highest by the NiTi wires.
5. The deflective force remains unchanged after nanocoating with Al_2O_3 for all the three types of archwires.

The results of this study show that nanocoating holds promise as a strategy to enhance the performance of superelastic orthodontic archwires.

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