

## Original Article

# The effect of zinc oxide nanoparticles deposition for friction reduction on orthodontic wires

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## ABSTRACT

**Background:** In the sliding technique, the reduced frictional forces are associated with rapid tooth movements and better control of the anchorage. Recently, wire coating with different nanoparticles has been proposed to decrease frictional forces. This *in vitro* study was carried out to coat stainless steel (SS) wires with zinc oxide (ZnO) nanoparticles in order to determine the effect of this coating on friction between wires and orthodontic brackets.

**Materials and Methods:** Eighty 0.016 inch and 0.019 inch  $\times$  0.025 inch SS wires with and without ZnO nanoparticles were used in 80 orthodontic brackets (0.018 and 0.022 systems). The coated wires were analyzed by SEM and X-Ray diffraction (XRD) observations. Kinetic friction between the wires and orthodontic brackets were calculated using a universal testing machine. Frictional forces were statistically analyzed using three-way ANOVA, one-way ANOVA, Student's *t*-test and Tukey multiple comparison tests.

**Results:** Coating with ZnO nanoparticles significantly influenced frictional force values ( $P < 0.0001$ ). In 0.019 inch  $\times$  0.025 inch wires, the frictional forces were  $1.6912 \pm 0.18868$  and  $3.4485 \pm 0.32389$  N in the coated and uncoated wires respectively, (51% reductions). In the 0.016 inch wires, the friction values were estimated to be  $1.5668 \pm 0.10703$  and  $2.56 \pm 0.34008$  N in the coated and uncoated conditions, respectively, (39% reductions).

**Conclusion:** Due to the positive effects of ZnO nanoparticle coating on decreasing frictional forces, these nanoparticles might offer a novel opportunity to significantly reduce friction during tooth movement.

**Key Words:** Kinetic friction, orthodontic wires and brackets, zinc oxide nanoparticles

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## INTRODUCTION

Orthodontic treatment is directly related to tooth movements. One common procedure to translate a tooth in the dental arch is sliding it along an arch-wire, which is associated with advantages such as decreased clinical treatment time, patient satisfaction, and three-dimensional control of tooth

movements.<sup>[1]</sup> However, a frictional force between the bracket and wire is unavoidable in the sliding procedure, with higher forces required to overcome it, in turn resulting in the anchorage control and creating some risks.<sup>[1,2]</sup> In orthodontic treatments, when the tooth-bonded brackets move along the wire, friction results from the load naturally applied on contact points.<sup>[3]</sup> Friction accompanies all sliding techniques and is considered an uncontrolled factor.<sup>[1,4]</sup> In sliding techniques, tipping, and up-righting tooth movements occur without any linear patterns. Following the application of a load on the tooth, tipping movements begin and an angle develops between the wire and the bracket's slot; when the angle reaches a certain critical range, a contact is made between the wire and bracket edges, consequently producing adhesion

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between the two metallic bodies. Then, the wire is subjected to a slow notching and plastic deformation; all these procedures lead to the inhibition of continuous tooth movements with numerous stops during tooth translation.<sup>[4]</sup> Overcoming this, obstacle requires excessive orthodontic forces of approximately 40-60%. At the same time, the increased forces increase the risk of anchorage loss, which is a major problem in orthodontic treatment. Tooth root resorption is another main disadvantage of increased load values.<sup>[5,6]</sup>

Some techniques have been developed to overcome this problem, such as use of wires of different metals, shapes, and sizes, as well as application of extra-oral forces or use of temporary implants.<sup>[6]</sup> Furthermore, the use of nanoparticles, invented in the 1990s, has been emphasized to decrease frictional forces between two metallic surfaces as excellent solid lubricants.<sup>[7-9]</sup> In order to utilize this characteristic of nanoparticles to decrease friction during orthodontic treatments, orthodontic wires or brackets must be coated with the nanoparticles.<sup>[7]</sup> Redlich *et al.* (2008) coated 0.019 inch × 0.025 inch orthodontic wires with inorganic fullerene-like nanoparticles of tungsten disulfide (WS<sub>2</sub>) and showed significantly reduced frictional forces on wires.<sup>[7]</sup> Naveh *et al.* (1995) reported reduced friction after coating Nickel-Titanium (NiTi) wires with nanoparticles of WS<sub>2</sub> in the laboratory.<sup>[10]</sup> Furthermore, stainless steel (SS) orthodontic wires were subjected to significantly decreased frictional forces when coated with nanoparticles of Carbone Nitride (CNx) as suggested by Wei *et al.*,<sup>[11]</sup> Goto *et al.* (2008) demonstrated a reduction in the frictional coefficient of zinc oxide (ZnO)-coated SS substrates in vacuum.<sup>[12]</sup>

Appropriate benefits of nanoparticles are related to the followings:

1. Rolling effects that cause two surfaces to slide on each other due to the spherical shape of the particles
2. Nanoparticles serve as spacers, preventing the contact between the two opposing surfaces
3. Third-body material transfer, which only occurs when the nanoparticles are released from the coated surfaces by electrolysis and transfer to the opposing metal (bracket).<sup>[7-9,13]</sup>

In the first stage of sliding, when there is no angle between the slot and wire, nanoparticles act as spacers and decrease the number of surface irregularities

which come in contact with each other, leading to a reduced lower coefficient of friction. However, when an angle is created between the bracket and the wire, and the binding process is developed, nanoparticles are released and a solid lubricant film is formed on sliding surfaces. In the higher load applications, the saliva is pushed out of the gap between the wire and the slot completely and it is only the solid lubricant film of nanoparticles, which decreases frictional forces and allows sliding to occur.<sup>[7-9,13]</sup>

Obviously, future clinical use of coated wires will depend on safe biocompatibility tests according to accepted procedures. Considering possible toxicity of WS<sub>2</sub>, new self-lubricating coatings, in which metals other than WS<sub>2</sub> have been used, should be prepared and analyzed.

The aim of the present study was to assess the effect of ZnO spherical nanoparticle coatings on reducing frictional forces in sliding tooth movements.

## MATERIALS AND METHODS

In this *in vitro* study, 80 orthodontic wires of 0.016 inch and 0.019 inch × 0.025 inch (American Orthodontics, USA) were used with and without ZnO nanoparticle coating. The studied devices included 40 SS brackets of the upper right centrals in 0.022 standard system (Ultratrimm, Dentaureum, Germany), 40 SS brackets of the upper right centrals in 0.018 standard system (Ultratrimm, Dentaureum, Germany), forty 0.016 inch SS straight wires (American Orthodontics, USA) with and without spherical ZnO nanoparticle coating as well as 40 rectangular 0.019 inch × 0.025 inch SS straight wires (American Orthodontics, USA) with and without spherical ZnO nanoparticle coating. Furthermore, a universal testing machine (Huns field Test Equipment, H5K Model; England) was used to exert tensile and sliding movements between the wires and brackets.

In order to coat wires with ZnO nanoparticles, the wires were first stored in an ultrasonic bath of ethanol solution for 30 min at 30°C. Then, 0.1 g of ZnO nanoparticles was added to the experimental tube containing ethanol solution and transferred to the water bath at 80°C after mixing.<sup>[14,15]</sup> Nanoparticles were evenly distributed in the ethanol solution, followed by immersion of the wires in the solution separately [Figure 1]. Different time intervals were selected for coating the wires with ZnO nanoparticles (10, 15, 20, 30, 40, 50, and 60 min).

SEM images of the wires confirmed ZnO nanoparticle coating in this method [Figure 2]. Furthermore, a pilot study and assessment of frictional forces showed that the time interval of 10 min was the best choice for nanoparticle coatings.

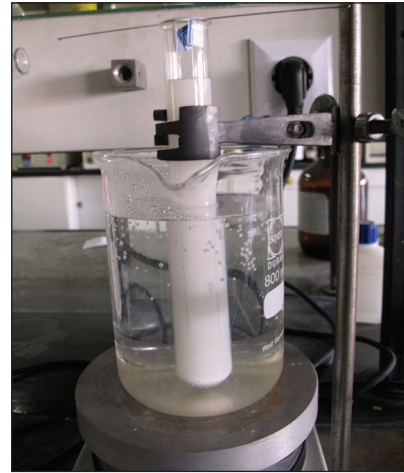
The friction force calculations during the sliding procedure were performed after nanoparticle coatings and preparation of wires. Central tooth brackets were bonded using a cyanoacrylate adhesive to an aluminum plate with a special bracket-mounting device in a fixed position. Then, the aluminum plate was fastened with screws to a notch created on a special device designed for bracket carrying. Then, it was attached to the base of a universal testing machine. In order to create an identical condition for all the specimens, the brackets were changed after each wire sliding. The aluminum plate was positioned in three different notches angulated at 0°, 5° and 10° to the long axis of the device, using a special screw holding instrument for the simulation of the 2<sup>nd</sup>-order bends.

Orthodontic wires were connected to the brackets by means of an elastomeric module (Dentaurum). The upper end of the wire was inserted into a tension load cell of the universal testing machine, and a 150-g weight was connected to the lower end of the wire. The wires were then pulled through the bracket at a cross-head speed of 0.5 mm/s for 25 s while, the frictional forces were calculated by means of the universal testing machine [Figure 3].<sup>[16]</sup> All the friction forces measured during this study were of kinetic type as no calculations were carried out at the baseline; however, after 0.1 s the friction values were calculated.<sup>[16]</sup>

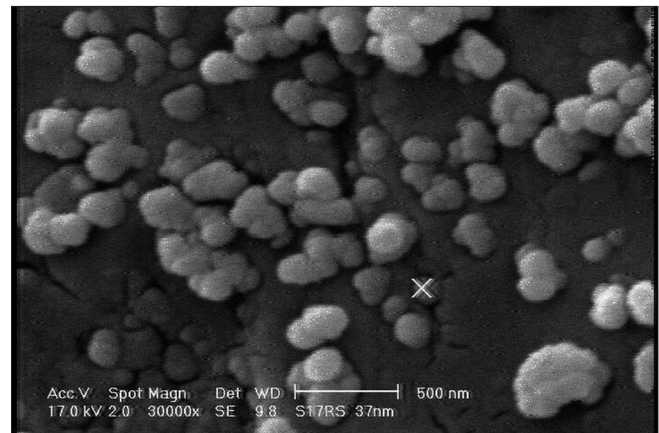
The mean and standard deviation of friction forces in each system, angulation and nanoparticle coating status were computed. Three-way ANOVA was used to analyze the effects of angulations, orthodontic systems and coating status on friction forces. Two- and three-group comparisons were carried out using Student's *t*-test and one-way ANOVA, respectively; in addition, a *post hoc* Tukey test was used for two-by-two comparisons.

## RESULTS

Three-way ANOVA showed that all the studied factors, including wire type ( $P < 0.0001$ ), the angle between the bracket and wire ( $P < 0.0001$ ), and coated versus uncoated wires ( $P < 0.0001$ ), significantly



**Figure 1:** Soaking of the wires in the solution for nanoparticle coating



**Figure 2:** SEM of a wire coated with zinc oxide



**Figure 3:** Friction measurements by means of a universal testing machine

affected the friction force; i.e., significantly different values of friction resistance were calculated regarding these variables.



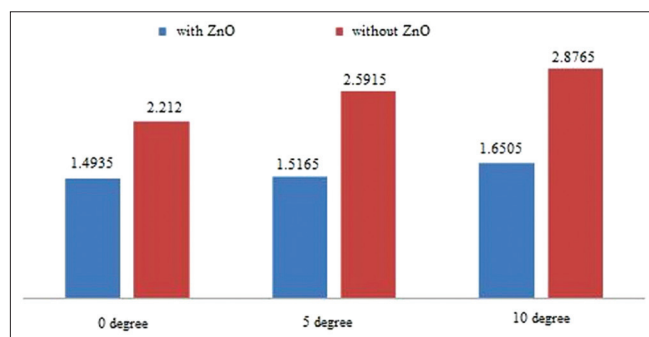
In 0.016 inch wires, the frictional force was estimated to be  $1.5668 \pm 0.107$  and  $2.56 \pm 0.3401$  N for the coated and uncoated wires in all the angles of the brackets and wires, respectively, suggesting significant reductions in friction (39%) following ZnO nanoparticle coating (Student's *t*-test:  $P < 0.0001$ ).

In 0.019 inch  $\times$  0.025 inch wires of 0.022 bracket system, the frictional forces were  $1.6912 \pm 0.18868$  and  $3.4485 \pm 0.32389$  N for the coated and uncoated wires, respectively, in all three angles, showing substantial decrease (51%) after ZnO nanoparticle coating (Student's *t*-test:  $P < 0.0001$ ) [Table 1].

In 0.016 inch wires, a significant reduction of friction force (32.48%) was observed at 0° for the ZnO-coated versus uncoated wires (Student's *t*-test:  $P < 0.0001$ ). At 5° angle, friction force on the coated versus uncoated wires exhibited a significant reduction of 41.48% (Student's *t*-test:  $P < 0.0001$ ). At 10° angle, a significant decrease in the friction force (41.23%) was demonstrated for coated versus uncoated wires (Student's *t*-test:  $P < 0.0001$ ) [Figure 4].

In 0.019  $\times$  25 wires of 0.022 SS straight system, a statistically significant decrease in frictional force (approximately 52.17%) was observed at 0° angle for the ZnO-coated versus uncoated wires (Student's *t*-test:  $P < 0.0001$ ). At 5° angle, the frictional force in ZnO-coated versus uncoated wires showed a significant reduction of 51.96% (Student's *t*-test:  $P < 0.0001$ ). At 10° angle, a statistically significant decrease in frictional forces (48.99%) was observed for the coated versus uncoated wires (Student's *t*-test:  $P < 0.0001$ ) [Figure 5]. Means, standard deviations, and standard errors of frictional forces are presented in Table 1 in each wire system, angulation and ZnO-coated or uncoated status.

At combined coated and uncoated wires of 0.018 systems, the frictional force was  $1.8528 \pm 0.427$  N at 0° angle,  $2.054 \pm 0.548$  N at 5°



**Figure 4:** Mean frictional force of 0.016 inch wire at 0°, 5° and 10°

angle, and  $2.2835 \pm 0.61$  N at 10° angle. Statistically, significant increases were observed in frictional forces with the increasing angles between the brackets and wires (one-way ANOVA:  $P < 0.002$ ). As shown by Tukey multiple comparisons test, the frictional force was differently reported at 0° and 10° angles ( $P < 0.001$ ) while it was not so between 0° and 5° angles ( $P = 0.22$ ) or 5° and 10° angles ( $P = 0.14$ ).

At both coated and uncoated wires of 0.022 systems, frictional forces were  $2.3878 \pm 0.87567$ ,  $2.5123 \pm 0.92183$  and  $2.8095 \pm 0.93553$  N at 0°, 5° and 10° angles, respectively. Slight and insignificant increases in frictional forces were found with increasing angles in this system (one-way ANOVA:  $P = 0.109$ ).

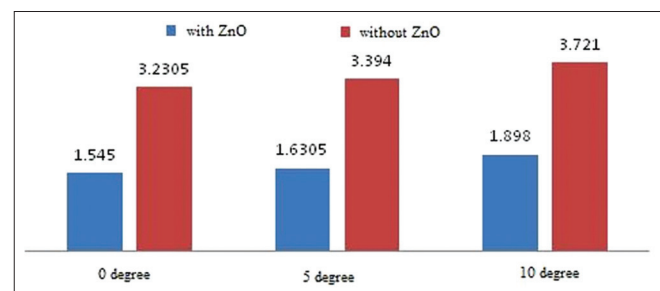
The total frictional forces were  $2.0634 \pm 0.55829$  and  $2.5698 \pm 0.92098$  N in 0.016 inch and 0.019 inch  $\times$  0.025 inch wire systems in three angles or coated and uncoated conditions. Wires of 0.019 inch  $\times$  0.025 inch system showed significantly higher frictional forces compared to 0.016 inch system (Student's *t*-test:  $P < 0.0001$ ).

## DISCUSSION

Nanoparticles are particles with a size range of 100 nm or less. Their chemical and physical characteristics are substantially different from the same materials of larger sizes.<sup>[17]</sup>

Along with the hypothesis suggesting frictional force reduction between orthodontic wires and brackets after coating with nanoparticles, we evaluated the effect of ZnO nanoparticle coating of wires on decreasing frictional forces.

The results showed a significant decrease in kinetic friction resistance to sliding in the ZnO-coated wires at different angles and both orthodontic systems of 0.018 and 0.022.



**Figure 5:** Mean frictional force of 0.019 inch  $\times$  0.025 inch wire at 0°, 5° and 10°

**Table 1: Means, standard deviations and standard errors of frictional forces at different degrees**

Wire	Angulation	ZnO coating	Mean	Standard deviation	Standard error
0.016	0°	With ZnO	1.4935	0.03133	0.007
		Without ZnO	2.212	0.31998	0.07155
		Total	1.8527	0.42747	0.06759
	5°	With ZnO	1.5165	0.06442	0.01441
		Without ZnO	2.5915	0.06523	0.01459
		Total	2.054	0.5481	0.08666
	10°	With ZnO	1.6905	0.07756	0.01734
		Without ZnO	2.8765	0.13612	0.03044
		Total	2.2835	0.61043	0.09652
Total	With ZnO	1.5668	0.10703	0.01382	
	Without ZnO	2.56	0.34008	0.0439	
	Total	2.0634	0.55829	0.05096	
0.019×0.025	0°	With ZnO	1.545	0.07857	0.01787
		Without ZnO	3.2305	0.26939	0.06024
		Total	2.3878	0.87567	0.13846
	5°	With ZnO	1.6305	0.09682	0.02165
		Without ZnO	3.394	0.31317	0.07003
		Total	2.5123	0.92183	0.14575
	10°	With ZnO	1.898	0.15364	0.03436
		Without ZnO	3.721	0.15423	0.03449
		Total	2.8095	0.93553	0.14792
Total	With ZnO	1.6912	0.18868	0.02436	
	Without ZnO	3.4485	0.32389	0.04181	
	Total	2.5698	0.92098	0.08407	
Total	0°	With ZnO	1.5193	0.06455	0.01021
		Without ZnO	2.7213	0.59264	0.0937
		Total	2.1203	0.73567	0.08225
	5°	With ZnO	1.5735	0.0996	0.01575
		Without ZnO	2.9927	0.46366	0.07331
		Total	2.2831	0.78802	0.0881
	10°	With ZnO	1.7943	0.1596	0.02523
		Without ZnO	3.2988	0.45109	0.07132
		Total	2.5465	0.82829	0.09261
Total	With ZnO	1.629	0.16501	0.01506	
	Without ZnO	3.0043	0.55531	0.05069	
	Total	2.3166	0.80119	0.05172	

ZnO: Zinc oxide

The mean total frictional force in both wires and systems were estimated to be 1.629 N for coated and 3.0043 N for uncoated wires, demonstrating a reduction of 46% following nanoparticle coating.

The frictional force significantly decreased to 32.48%, 41.48% and 41.23% at 0°, 5° and 10° angles, respectively, following ZnO nanoparticle coating on 0.016 inch wires compared to the same uncoated wires. In addition, the mean friction resistance significantly decreased by 52.17%, 52.96%, and 48.99% at 0°, 5° and 10° angles, respectively, after ZnO nanoparticle coating on 0.019 inch × 0.025 inch wires compared to the same uncoated wires.

The mean frictional forces in 0.019 inch × 0.025 inch wires showed 51% of reduction after nanoparticle

coating. Furthermore, the mean frictional forces in 0.016 inch wires showed 39% of reduction after coating.

The mechanism by which the friction force is reduced after nanoparticle coating has been explained by Rapoport *et al.* (2003)<sup>[18]</sup> and Cizaire *et al.*<sup>[19]</sup>

During the first phase, when there is no angle between the bracket slot and the wire, i.e., when the bracket slot translates parallel to the wire, nanoparticles act as spacers decreasing the number of surface irregularities which come into contact with each other, leading to a decreased friction coefficient. As the angle between the slot and wire increases, the force increases at the edges of the slot, resulting in more friction resistance at the uncoated wire. At this

point, some nanoparticles seem to exfoliate resulting in dry lubrication of the sliding process on the wires coated with nanoparticles.<sup>[7]</sup> When the two materials are made of SS, like the uncoated wires, the friction coefficient increases with time, possibly due to the tribochemical reactions leading to oxidation.

When the Nano sheets are subjected to higher forces at interfacial areas, the sliding takes place between these thin sheets of the exfoliated nanoparticles at the interfaces, consequently reducing the coefficient of friction.<sup>[20]</sup> In addition, ZnO nanoparticles act as a protection against the oxidation of metal surfaces, consequently decreasing friction resistance.

Prasad *et al.* (1997) and Zabinski *et al.* (2000) concluded that decreased coefficient of friction after ZnO coating is related to their nanostructure properties which increase lubricating characteristics of the surfaces by participating in their plastic deformation and reducing friction in turn.<sup>[21,22]</sup> Goto *et al.* (2011) demonstrated, using X-ray diffraction spectroscopy, that crystalline preferred orientation of ZnO nanoparticles had a significant effect on their low frictional properties.<sup>[23]</sup>

Redlich *et al.* (2008) studied the friction resistance of 0.019 inch  $\times$  0.025 inch orthodontic wires after coating with fullerene-like nanoparticles of WS<sub>2</sub> and showed substantial reduction of frictional forces after nanoparticle coating, somehow similar to our findings.<sup>[7]</sup>

Katz *et al.* (2006) showed that coating with fullerene-like WS<sub>2</sub> nanoparticles significantly reduces arch-wire friction with the possible alleviation of the adverse complications of orthodontic treatment.<sup>[24]</sup> These studies were carried out using fullerene-like nanoparticles of WS<sub>2</sub> which is somehow different from ZnO nanoparticles used in the present study, though their effects on decreasing friction resistance were similar. One advantage of ZnO particles compared to WS<sub>2</sub> is their biocompatibility with and safeness for human tissues.<sup>[25]</sup>

The friction coefficient of compact ZnO in high temperatures is about 0.65. ZnO is not able to create a lubricious surface in powder or compact disc forms; however, nanostructure ZnO is capable of developing lubricious surfaces with a friction coefficient of 0.2.<sup>[26]</sup> It seems that nanoparticle coatings on SS brackets and wires lead to reduced frictional resistance due to the removal of corrosion factors, too.

In the present study, all the frictional forces were of kinetic type as no measurements were carried out at baseline and rather, all the calculations were performed after 0.1s. Some argue that as the movement takes place and the applied forces overcome the static friction resistance, calculation of static friction becomes more important than kinetic friction.<sup>[16]</sup> Some others suggest a study of kinetic frictional force in the tooth sliding movements.<sup>[27-29]</sup> During space closure procedures, teeth usually move and overcoming the static friction resistance does not require more time. In addition, overcoming static friction cannot lead to tooth movement and it is the biologic resistance of periodontium that plays an important role. Furthermore, the limitations of simulating kinetic friction assessments are fewer than static friction calculations. Regarding the above-mentioned arguments, kinetic friction was measured in the present study.

Due to the positive effects of nanoparticle coatings on decreasing frictional forces between orthodontic wires and brackets, the coatings can be applied to other orthodontic appliances and materials, such as conventional brackets and self-ligating systems and to initial treatment of flexible wires like NiTi arches. With the improvement of coating methods and their approval for use in the oral cavity, friction during orthodontic treatments can significantly decrease, resulting in better anchorage control with the consequent reduced treatment time and risk of root resorption. However, further studies are required to assess cellular toxicity of nanoparticles or their effect on different organs in order to approve their safety.

## CONCLUSION

Following ZnO nanoparticle coating, the frictional force between brackets and wires significantly decreased in all the angulations and systems. Due to the positive effects of ZnO nanoparticle coating on decreasing frictional forces, these nanoparticles might offer a novel opportunity to significantly reduce friction during tooth movement and the consequent better anchorage control, reduced treatment time and risk of root resorption.

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