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The effect of various nanoparticle coating on the frictional resistance at orthodontic wire and bracket interface: A systematic review

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Abstract

This systematic review was aimed to test the null hypothesis that coating of orthodontic wires with nanoparticles does not affect the frictional properties at bracket-wire interface. Electronic database searches were performed up to September 2020. *In vitro* studies were considered for reviewing process. Study selection, data extraction, risk of bias assessment was performed during reviewing process. Only qualitative analyses of included literature were done due to the presence of heterogeneity among the studies. Out of 1,068 retrieved records, nine studies satisfied the inclusion criteria and included in this review. Studies were assessed at low risk to high risk of bias according to certain parameters. Wide variety of nanoparticles were used for surface coating of orthodontic wires of variable sizes, shapes, and materials like stainless steel, NiTi, and TMA and placed into the slots of different types of orthodontic brackets to evaluate the alteration in frictional and other mechanical properties. Most of the studies clearly indicate that coating with nanoparticles decreases the friction between wire and bracket interface under specified *in vitro* conditions. Furthermore, among the nine included studies, only two considered evaluation of effect of coated brackets on frictional and other mechanical properties and results were heterogeneous. The null hypothesis is rejected and it is concluded that the wires coated with nanoparticles might offer a novel opportunity to substantially reduce frictional resistance at bracket-wire interface during tooth movement. Further studies are necessary to strengthen the evidence regarding effect of coated brackets on frictional properties.

Keywords:

Coating methods, frictional properties, nanoparticles, orthodontic brackets, orthodontic wires

Introduction

Over the past 100 years, improvements in the field of mechanotherapy and treatment philosophy have largely been made possible with the emergence of newer orthodontic materials. Archwire materials form a larger part of this change, and a thorough knowledge of biomechanical and clinical applications of the archwire is required for selecting the same. Several properties such as esthetics, friction, biostability, formability,

weldability, resilience and spring back, etc., should be considered during the search of an ideal archwire. Friction plays an important role among the alloy's characteristics that alter the behaviour of the archwire.

During alignment and space closure in the dental arch, sliding a tooth along an orthodontic wire is a common clinical procedure. Whenever sliding occurs, a frictional force is generated between the wire and the orthodontic bracket.^[1] Friction is defined as the resisting force tangential to the common boundaries between two or more bodies, when under the action of an

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external force, one body moves or tends to move relative to the surface of the other".^[2] In 1976, Farrant *et al.*^[3] briefly described role of friction in orthodontics as teeth are moved via a traction force along an archwire. In case of orthodontic mechanotherapy, a biological tissue response with resultant tooth movement will occur only when the applied forces adequately overcome the friction at the bracket--wire interface.^[4] The lost portion of the applied force (because of the resistance to sliding) can range from as low as 12% to as high as 60%.^[5] High frictional forces will affect the efficiency of the system severely, and this leads to the extension of treatment time or the outcome becomes compromised because of little or no tooth movement.

In 1992, Kusy *et al.*,^[6] made attempts to alter or modify the surface properties of orthodontic materials assuming the interaction of the surface chemistry of the bracket slot with the archwire may affect the friction. Surface films are most powerful modifiers of friction and it can change friction by as much as factor of 10.^[7,8] To improve the tribological properties, various surface treating techniques have been applied on the orthodontic appliances with the evolution in the material engineering. The objective of this systemic review was to resolve the null hypothesis that coating of orthodontic wires does not have any effect on frictional properties at bracket--wire interface.

Materials and Methods

This systematic review was conducted according to well-established guidelines of PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) and Cochrane Handbook of systematic review.^[9,10] Protocol was constructed according to recommended guidelines but no registration was performed on publicly accessible database.

Search strategy

An electronic search of scientific literature was performed without restriction to time and language. All the original research articles, review articles, published bibliographies, unpublished research works and relevant citations related to surface modification of orthodontic wires were checked for relevant information, used in this review. Reference list of included studies were also explored for any relevant articles. Electronic and manual search were conducted on database including PubMed, Scopus, Science direct, Google scholar, and Web of science up to September 2020. A combination of search terms "Orthodontic wires," "NiTi wires," "Stainless steel wires," "Beta Titanium wires," "coated orthodontic wires," "frictional behavior of orthodontic wires," "mechanical properties of coated wires," "surface modification of orthodontic wires" and "surface characteristic of coated orthodontic wire" were used.

Eligibility criteria (PICOS scheme)

Participants (Specimen)

- *In vitro* studies involving surface modification of received orthodontic wires and brackets by nanoparticles to improve frictional properties and other mechanical/physical properties.

Intervention

- Studies describing the specific coating method used for surface modification of orthodontic wires.

Comparison

- Studies comparing coated wire's frictional and other mechanical properties with control group (uncoated wire).

Outcome

- Changes in frictional properties as a primary outcome, while other mechanical properties as a secondary outcome.

Study design

- *In vitro* studies.

Exclusion criteria

- Case reports, preliminary reports, case series, letter to editor, comments, repetitive publications, systematic review and abstracts.
- Studies evaluating frictional properties without control group.
- Studies done on retrieved wires after clinical use.
- Studies involving coating done for esthetic purposes.
- Studies considering biological properties of surface modified orthodontic wires.

Study selection and data extraction

Abstracts of the retrieved results were scrutinized, and papers that seemed to meet the initial selection criteria defined (*in vitro* studies that addressed surface modification by coating nanoparticles to improve frictional properties of orthodontic wires) were identified. Papers were excluded at this stage if they were descriptive, editorial, letter to editor, *in vivo*, or were studying other properties of surface modified orthodontic wires rather than friction. Full articles were obtained from the abstracts/titles that met the inclusion criteria. The selections were then discussed, and discrepancies were resolved. Furthermore, a secondary (manual) search was then performed by going through the reference lists of the selected articles to identify any paper that met the inclusion criteria but was missed by the electronic searches.

Risk of bias assessment

Two authors (NKS and VKS) independently evaluated the risk of bias of each included study considering a score described in previous systematic reviews of

in vitro studies.^[11,12] The description of the following parameters was checked in each study: randomization of the specimens for experimental and control groups, prior sample size calculation, similar cross-section or size of specimen, intervention defined, control group taken, statistical analysis performed, blinding of observer, commercial or noncommercial specimen specified, all possible outcome reported or not, loss of specimen reported or not. If the parameter was described on the text, the study received a “yes” on that specified parameter; otherwise, it had a “no”. The risk of bias was classified according to the sum of “yes” received as follows: 1–3 = high, 4–5 = moderate, 6–10 = low risk of bias. Unclear and no information entries were considered as of some concern if domain question seems to affect the outcome of the study otherwise marked under low-risk category accordingly. Any disagreements were resolved by discussion with other three authors (IMP, TPC and DS).

Synthesis of result

Studies were considered for quantitative analysis if presented with sufficient homogenous data with respect to participants, intervention and outcomes. Otherwise, qualitative assessment of the data would have been undertaken. Data on the alteration of frictional and mechanical properties due to application of different coating materials were planned to be expressed as risk ratios (RR) for dichotomous data and standardized mean difference (SMD) for continuous data, together with the relevant 95% confidence intervals (CI). Random effect model was planned to combine the data.

Results

Study selection

The search results based on electronic search yielded 1,068 articles initially. After exclusion of duplicates, 953 studies remained. After screening of titles and abstracts 924 articles were scrutinized against the selection criteria. Then, the full text of 29 articles were obtained and assessed for eligibility, after applying the eligibility criteria. A total of 9 publications were finally included in this systematic review. References and citations of final included articles were also explored for any relevant studies. The flow chart summarizing the search strategy is provided in Figure 1.

Characteristics of included studies

The characteristics of various studies are mentioned in Table 1. A wide variety of nanoparticles were used for surface coating of orthodontic wires that include Diamond like carbon (DLC), Fullerene like nanoparticles of tungsten disulfide (IF-WS₂), Spherical Zinc oxide (ZnO), Titanium aluminium nitride (TiAlN),

tungsten carbide (WC/C), Molybdenum and tungsten disulfide (IF-WS₂) and nanoparticles of silver (Ag). All the included studies conducted *in vitro* experiment by manual coating of orthodontic wires with description of the specific coating method. Nanoparticles after coating were evaluated by scanning electron microscope (SEM) associated with X-ray diffractometry and X-ray spectrometry. Most of the studies employed universal testing machine to carry out mechanical measurements such as friction, load deflection and elastic modulus for coated and uncoated wires.

Results of individual studies and qualitative synthesis

Due to presence of heterogeneous data with respect to participants, interventions and outcomes, only qualitative analysis of the data has been done. Differences were observed in the following variables- Coating material and method, Wires used with respect to dimension and type, Bracket type and prescription, force applied, load cell, and weight, Bracket--wire angulations. Results of the individual *in vitro* studies to evaluate friction and other properties are reported in Table 2 and details of the outcome of frictional measurements are enumerated in Table 3. For the descriptive purpose, outcomes were divided into following categories.

Different coatings and friction. Among the included studies three of them used fullerene like nanoparticles of tungsten disulfide which were deposited on different wire combinations.^[13-15] One study^[13] used fullerene like nanoparticles of nickel-phosphorous (Ni-P) and tungsten disulfide (IF-WS₂) for coating stainless steel archwires and the results showed that the coated archwires exhibited a significant reduction of the frictional force. Another study^[14] which used Cobalt (Co) and fullerene like tungsten disulfide (IF-WS₂) for coating on nickel titanium archwires demonstrated a decline of static and kinetic friction coefficients with respect to the uncoated wires. Gracco *et al.*^[15] incorporated nanoparticles of molybdenum (MoS₂) and tungsten disulfide (WS₂) and the wires coated with Ni + MoS₂ (Nickel + molybdenum) and Ni + WS₂ (Nickel + tungsten disulfide) films have friction values significantly lower than uncoated wires. DLC (diamond like carbon) nanoparticles were used in three studies.^[16-18] All the three studies reported that the frictional values are lower than the uncoated wires. Zhang *et al.*^[17] reported that the kinetic friction coefficient of DLC-coated wires were reduced compared with the control wires but the static friction coefficient of the nitro-carbarized wires was significantly lower than those of the DLC-coated wires and uncoated wires. One study^[19] used ZnO (Zinc oxide) nanoparticles for surface modification and showed that deposition of ZnO on stainless steel wires does not affect the frictional properties. Krishnan *et al.*^[20] used TiAlN (titanium

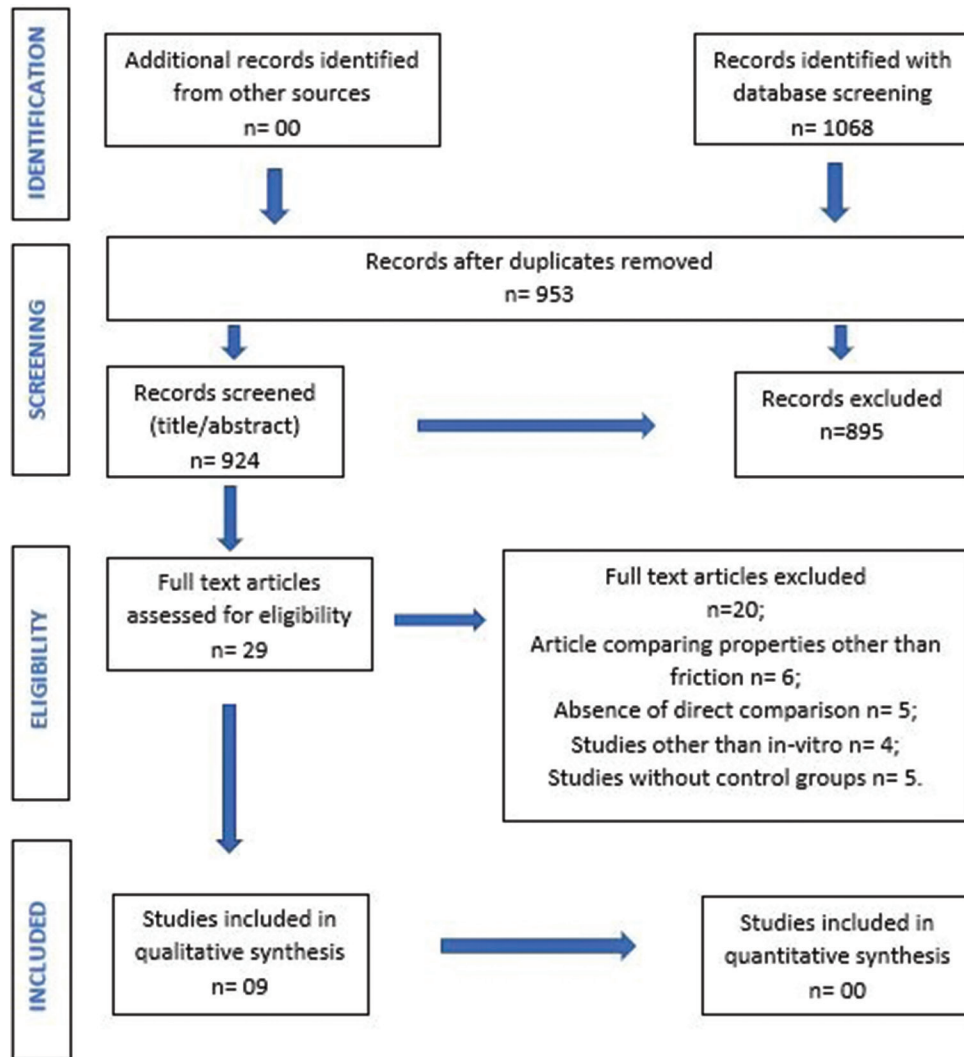


Figure 1: Flowchart diagram of search strategy, according to PRISMA guideline)

aluminium nitride) and WC/C (tungsten carbide) for coating and the results indicated that frictional properties of WC/C-coated wires were reduced compared with TiAlN coated and uncoated wires. Another study^[21] used nanoparticles of silver (Ag) as coating material and revealed that the silver coated wire did not show any change in the frictional resistance when compared with uncoated wire.

Friction in stainless steel archwires. Most of the included studies got the measure of frictional resistance of coated stainless steel archwires. Among them, 5 studies^[13,15-18] substantiated that stainless steel archwires when coated with nanoparticles such as DLC and fullerene like nanoparticles resulted in lower frictional forces and other 2 studies validated that stainless steel archwires showed no improvement in frictional characteristics when coated with nanoparticles such as ZnO^[19] and Ag.^[21] Only one study^[16] coated DLC nanoparticles on both stainless steel and nickel titanium wires and revealed that DLC

coated stainless steel wires exhibited significantly less frictional force.

Friction in Nickel titanium archwires. Two studies^[14,16] evaluated the frictional resistance of coated nickel titanium wires. One study^[14] used fullerene like tungsten disulfide and the other study^[16] used DLC nanoparticles. Both of them revealed that there is improvement in frictional force after coating when compared with uncoated wires.

Friction in other archwires. Only one study^[20] deposited TiAlN and WC/C tungsten carbide over beta titanium wires and reported that WC/C coated wires had reduced frictional forces when compared with TiAlN coated and uncoated wires.

Wire and bracket combination. Only two of the nine studies investigated the effect of nanoparticle coating on brackets in frictional resistance.^[18,19] One study^[18]

Table 1: Characteristics of various studies

Study	Study group and control group	Coating material and method	Bracket type and prescription	Examination methods	Testing apparatus (force applied, load cell, weight)	Crosshead speed Ligature type Bracket wire angulations and load values Testing conditions
Redlich <i>et al.</i> (2008) ^[13]	Group 1- uncoated S. S wire Group 2- Ni+IF-WS ₂ coated S. S wire	Fullerene like nanoparticles (IF-WS ₂) of Tungsten disulfide by Electroplating process	Upper right central incisor bracket, 0.022 x 0.028", straight wire brackets.	1. SEM + X-ray diffraction- Characteristics of coated films. 2. Ball on flat device- Tribiological tests. 3. UTM Instron machine- Friction. 4. Raman microscope- Adhesion properties.	Instron 4502 testing machine, wire attached to 10 N load cell and 150 gm weight	10 mm/min for a distance of 5 mm, Elastomeric ligature, 0°, 5°, 10° and Dry condition
Somorodnitsky <i>et al.</i> (2009) ^[14]	Group 1- uncoated NiTi wire Group 2- Co+IF-WS ₂ coated NiTi wire	Cobalt and fullerene like tungsten disulfide (IF-WS ₂) by Electrodeposition	Self- ligating brackets	1. SEM- Surface characterization. 2. X-ray diffractometry- Chemical analysis of coating composition. 3. Ball on flat set up measured using UTM- Friction.	Twin column testing machine, LR 10 K, Instron system with load cell 10 KN	5 mm/min for a distance of 5 mm, - 2°, 3,8°, 5° Load of 0.5 N and Dry condition
Muguruma <i>et al.</i> (2011) ^[15]	Group 1- DLC coated NiTi wire. Group 2- uncoated NiTi wire. Group 3- DLC coated S. S wire. Group 4- uncoated S. S wire.	Diamond like carbon (DLC) using Plasma -Based Ion Implantation and/or Deposition (PBIID)	Conventional and self-ligating bracket	1.3D SEM- Surface characteristics of DLC layers. 2. Nano indentation test- Hardness and elastic modulus. 3. Custom fabricated device attached to UTM- Friction.	Custom fabricated friction measuring device attached to universal testing machine with load cell of 20N	- - 0° and 10°, Dry condition and room temperature
Krishnan <i>et al.</i> (2012) ^[16]	Group 1- BTUC 1 Group 2- BTUC 2 Group 3- BTUC 3	Titanium aluminium nitride (TiAlN) + Tungsten carbide by Physical Vapor Deposition (PVD)	Edgewise brackets 0.022x 0.028" slot	1. SEM- Cross sectional characteristics. 2. UTM- Load deflection rate and Friction.	Instron universal testing machine with full scale load set at 5N	10 mm/min, Elastomeric ligature, 0.5 N and 1N Dry condition
Kang <i>et al.</i> (2015) ^[17]	Group 1 -W _{CON} -B _{CON} Group 2 -W _{CON} -B _{DLC} Group 3 -W _{DLC} -B _{CON} Group 4 -W _{DLC} -B _{DLC}	Diamond like carbon (DLC) by mirror-confinement-type electron cyclotron resonance (MCECR) plasma sputtering	0.022" slot upper premolar bracket	1. X-ray photoelectron spectroscopy-Bonding states of DLC films. 2. SEM- Cross sectional observation of films. 3. Self developed friction tester using UTM- Friction.	Self developed friction tester	Tests were run with ±150 µm displacement amplitude at a frequency of 0.5 Hz, - 1N Ambient air and artificial saliva and room temperature
Zhang <i>et al.</i> (2016) ^[18]	Group 1- uncoated S. S wire Group 2- DLC coated S. S wire Group 3- Nitrocarborized S. S wire	Diamond like carbon DLC-by Plasma- Enhanced Chemical Vapor Deposition (PECVD)	Maxillary 1 st premolar Conventional S. S bracket, 0.022" slot.	1. Raman microscope- Surface characteristics of DLC coating. 2. SEM-Cross sectional topography of wires. 3. Vickers micro hardness tester- Micro hardness. 4. Nanoindentation test -Elastic modulus 5. UTM- friction.	Universal testing machine, Instron ltd	10 mm/min for distance of 20 mm Elastomeric ligature - Dry condition at 25°C

Contd...

Table 1: Contd...

Study	Study group and control group	Coating material and method	Bracket type and prescription	Examination methods	Testing apparatus (force applied, load cell, weight)	Crosshead speed Bracket wire angulations and load values Testing conditions	Ligature type
Behroozian <i>et al.</i> (2016) ^[19]	Group 1- ZZ coated wires of bracket. Group 2- OO uncoated wire and bracket. Group 3- OZ uncoated wire and bracket. Group 4- ZO coated wire and uncoated bracket.	Spherical ZnO nanoparticles by Electro deposition	Central incisor bracket 0.022" slot ceramic bracket	1. SEM- Analysis of deposited ZnO nanoparticles. 2. UTM- Friction.	Universal testing Machine with its lower end attached to 150 g sinker.	Pulled at a rate of 0.5 mm/sec for 25 secs Elastomeric modules 0° Wet condition in artificial saliva	
Shah <i>et al.</i> (2018) ^[20]	Group 1-0.017x0.025" coated S. S wire Group 2-0.017x0.025" uncoated S. S wire Group 3-0.019x0.025" coated S. S wire Group 4-0.019x0.025" uncoated S. S wire	Silver nanoparticles by thermal vacuum evaporation PVD- coating technique	Central incisor bracket, conventional bracket 0.022x0.028" slot	UTM- Friction measurements.	Friction testing device attached to universal testing machine	- Elastomeric ligature - Dry condition at room temperature	
Gracco <i>et al.</i> (2019) ^[21]	Group 1- uncoated S. S wire Group 2- Ni film coated S. S wire. Group 3- Ni+MoS ₂ coated S. S wire. Group 4- Ni+WS ₂ coated S. S wire.	Molybdenum and tungsten disulfide (MoS ₂ and WS ₂) by electrodeposition	2 types of central incisor bracket, self-ligating (interactive and passive)	1. SEM and EDS-Analysis of morphology and chemical composition of deposited film 2. UTM – Friction measurements.	Universal testing machine with load cell 100N of Instron 4502 and lowered to a weight of 136 g	5 mm/min for a distance of 5 mm - 0° and 5° Dry and wet condition with artificial saliva at 21°C	

SS (stainless steel), NiTi (nickel titanium), DLC (diamond like carbon), TiAIN (titanium aluminium nitride), WC/C (tungsten carbide), IF-WS₂ (fullerene like tungsten disulfide), ZnO (zinc oxide), PBIID (Plasma- based ion implantation/deposition), MCECR (Mirror- confinement- type electron cyclotron resonance), PVD (Physical vapourdeposition), SEM (scanning electron microscope), UTM (universal testing machine), EDS (energy-dispersive X-ray spectrometry)

Table 2: Overall result of individual studies

Study and publication	Surface characteristics	Friction	Surface hardness	Load deflection	Elastic modulus
Redlich <i>et al.</i> (2008) ^[13]	X-ray diffraction and SEM shows Poor crystallinity. Adhesion-remains unaffected after bending	Decreased friction coefficient by 50% -coated group Increased friction coefficient in uncoated group	----	----	----
Somorodnitzky <i>et al.</i> (2009) ^[14]	Well-defined continuous coating Bending test-undamaged coating without cracks after bending test	Reduction of 20 to 30% of static and kinetic friction in coated and increased static and kinetic friction in uncoated group.	----	----	----
Muguruma <i>et al.</i> (2011) ^[15]	Surface roughness not affected by coating	Significantly reduced friction in coated NiTi and S. S group compared with control.	----	----	1944 GPa 74.9 GPa 277.4 GPa 82.9 GPa
Krishnan <i>et al.</i> (2012) ^[16]	The Coating as well its varied thickness from each group of specimens was clearly visible and minor drawing line was visible after sliding.	Group 1-more friction Group 2-less friction compared to group 1 Group 3-less friction group 1 and group 2	----	Group 2 and 3 showed low deflection rate compared to Group 1	----
Kang <i>et al.</i> (2015) ^[17]	Slight decrease in roughness which was statistically insignificant	$W_{CON}-B_{CON}$ and $W_{DLC}-B_{DLC}$ =lowest frictional coefficient. $W_{DLC}-B_{CON}$ and $W_{DLC}-B_{DLC}$ =high frictional coefficient.	Extensive wear and plastic deformation in $W_{CON}-B_{CON}$ and $W_{CON}-B_{DLC}$	----	----
Zhang <i>et al.</i> (2016) ^[18]	SEM Shows- 1 μ m of coating thickness and ultra fine crystal grains. Nitrocarborized-relatively smooth compared to control.	Nitrocarborized- significantly decreased by 22% than control group DLC-friction decreased compared to control group	DLC-685.17H _v Nitro-119.58 H _v Control 468.4H _v	----	DLC-74.17 Gpa Nitro-206.03 Gpa Control-204.2Gpa
Behroozian <i>et al.</i> (2016) ^[19]	Uniform distribution of nano particles	ZZ- maximum frictional force OZ-minimum frictional force ZO- no significant difference OO-no significant difference	----	----	----
Shah <i>et al.</i> (2018) ^[20]	----	Group 3 shows significant reduction in friction and others showed no significant reduction in friction	----	----	----
Gracco <i>et al.</i> (2019) ^[21]	Homogenous well-defined continuous coatings with spherical and cylindrical structures.	Group 3 and 4 shows lower friction values when compared with other group. But there is no significant difference between group 3 and group 4.	----	----	----

WCON-BCON (conventional S. S wire and bracket), WCON-BDLC (conventional S. S wire and DLC coated bracket), WDLC-BCON (DLC coated S. S wire and conventional bracket), WDLC-BDLC (DLC coated S. S wire and bracket), OO- uncoated S. S wire and uncoated bracket, ZO- coated S. S wire and uncoated bracket, OZ- uncoated S. S wire and coated bracket, ZZ- coated S. S wire and coated bracket

coated DLC nanoparticle on stainless steel brackets and conveyed that DLC coated brackets when combined with DLC coated wires exhibited a reduction in frictional force otherwise DLC coated brackets alone does not affect the frictional resistance. Another study^[19] which coated ZnO nanoparticles on ceramic brackets revealed that the presence of ZnO nanoparticle coating on ceramic brackets was effective in terms of frictional resistance than the coating on wire. According to Muguruma *et al.*,^[16] self-ligating brackets showed significantly less frictional force than the conventional brackets when combined with coated wires. Gracco *et al.*,^[15] in their study, employed two kinds of self-ligating brackets that is interactive (In-Ovation) and passive (Damon-Q) self-ligating brackets and the results suggested that

interactive self-ligating brackets gave better performance than passive self-ligating brackets in terms of friction.

Other reported outcome. On observing the evaluation of other properties other than friction, Zhang *et al.*^[17] reported that after surface modification, microhardness of the DLC-coated wires (685.17 Hv) was increased 1.46 times compared with the control wires (468.42 Hv). On the other hand, the elastic modulus for the DLC-coated stainless steel wire was less than that of the as-received stainless steel wire [277.39 ± 16.33Gpa (uncoated S. S wire) 194.44 ± 9.09Gpa (DLC coated S. S wire)]. Surface hardness were not evaluated for other nanoparticles. As reported by Krishnan *et al.*,^[20] the load deflection rate was significantly reduced by both TiAlN and WC/C

Table 3: Result of individual studies to evaluate friction

Study	Outcome		Result				P
	Friction coefficient (N)	Contact angle	Group 1 (uncoated S. S wire)	Group 2 (Ni + IF-WS ₂ coated S. S wire)	Group 1 (uncoated NiTi wire)	Group 2 (Co + IF-WS ₂ coated NiTi wire)	
Redlich et al. (2008) ^[13]	0°	1.32±0.12 N		1.10±0.06 N			<0.05
	5°	2.95±0.09 N		1.58±0.25 N			<
	10°	4.00±0.19 N		1.85±0.21 N			0.001
				Kinetic			
	Static and kinetic coefficient of friction (N)	Contact angle	Group 1 (uncoated NiTi wire)	Group 2 (Co + IF-WS ₂ coated NiTi wire)	Group 1 (uncoated NiTi wire)	Group 2 (Co + IF-WS ₂ coated NiTi wire)	
Somorodnitsky et al. (2009) ^[14]	2°	0.103±0.3		0.083±0.01	0.103±0.02	0.077±0.01	
	3.8°	0.109±0.02		0.086±0.02	0.099±0.01	0.066±0.01	
	5°	—		0.080±0.02	—	0.061±0.01	
				Wire			
	Static frictional force (g)	Contact angle	Bracket	Group 2 and 4 (uncoated)	Group 1 and 3 (DLC coated)		P
Muguruma et al. (2011) ^[15]	0°	Brand 1 (self ligating)	0.016 NiTi	6.63±2.15	6.12±1.32	0.796	
			0.018 NiTi	7.39±1.88	6.88±1.23	0.631	
			0.19 x 0.025 S. S	6.63±1.78	9.43±1.23	0.003	
	Brand 2 (self ligating)	0.016 NiTi	6.88±1.72	6.88±2.42	0.971		
		0.018 NiTi	7.14±1.61	6.37±1.8	0.481		
		0.19 x 0.025 S. S	46.65±8.92	46.65±7.11	0.739		
	Brand 3 (conventional)	0.016 NiTi	125.68±26.14	98.66±13.17	0.011		
		0.018 NiTi	123.13±33.59	79.03±7.88	0.001		
		0.19 x 0.025 S. S	120.58±16.04	101.89±11.71	0.015		
	10°	Brand 1 (self ligating)	0.016 NiTi	54.55±14.08	31.61±5.79	0.001	
			0.018 NiTi	139.19±40.7	110.89±15.91	0.063	
			0.019 x 0.025 S. S	298.01±45.82	254.42±37.19	0.019	
	Brand 2 (self ligating)	0.016 NiTi	41.3±11.82	26±3.56	0.0001		
		0.018 NiTi	117.52±43.64	88.21±11.41	0.063		
		0.019 x 0.025 S. S	235.04±41.76	187.88±22.1	0.002		
Brand 3 (conventional)	0.016 NiTi	191.45±30.2	113.95±14.47	0.0001			
	0.018 NiTi	211.08±29.55	182.78±22.48	0.043			
	0.19 x 0.025 S. S	353.84±68.57	336±42.96	0.739			
				Group 3 (BTUC 3)			
	Coefficient of friction	Force application	Group 1 (BTUC 1)	Group 2 (BTUC 2)	Group 3 (BTUC 3)	P	
Krishnan et al. (2012) ^[16]	0.5 N	1N	0.108±0.015	0.162±0.031	0.086±0.008	< 0.05	
			0.125±0.014	0.112±0.006	0.067±0.005	< 0.05	
				Fretting condition			
	Friction coefficient (μ)	Force application	Group 1 (WCON-BCON)	Group 2 (WCON-BDLC)	Group 3 (WDLG-BCON)	Group 4 (WDLG-BDLC)	P
Kang et al. (2015) ^[17]	1N	Dry	0.60	0.53	0.13	0.11	
			0.40	0.38	0.12	0.12	
				Ambient air			

Contd...

Table 3: Contd...

Static and kinetic friction coefficient	Group 1 (uncoated S. S wire)		Group 2 (DLC coated S. S wire)		Group 3 (Nitrocarburized S. S wire)		
	static	kinetic	static	kinetic	static	kinetic	
Zhang <i>et al.</i> (2016) ^[19]	105.40±10.89	47.63±9.38	107.33±27.28	28.24±9.17	89.34±13.84	48.43±11.03	
Frictional force (N)	Contact angle		Group 1 (OO- uncoated S. S wire and uncoated bracket)	Group 2 (ZO- coated S. S wire and uncoated bracket)	Group 3 (OZ- uncoated S. S wire and coated bracket)	Group 4 (ZZ- coated S. S wire and coated bracket)	
	2.70±0.2 N	0°	2.65±0.2N	2.18±0.5N (P<0.05)	3.07±0.4 N (P<0.05)		
Load values of frictional resistance (N)	Group 1 [0.017x0.025" coated S. S wire]		Group 2 (0.017x0.025" uncoated S. S wire)		Group 3 (0.019x0.025" coated S. S wire)		
	1.8±0.83 N		1.46±0.80 N (P=0.854)	1.55±0.32 N (P=0.711)	2.56±0.99 N (P=0.002)		
Frictional force (N)	Contact angle	conditions	Brackets	Group 1 (uncoated S. S wire)	Group 2 (Ni coated S. S wire)	Group 3 (Ni + MoS ₂ coated S. S wire)	Group 4 (Ni + WS ₂ coated S. S wire)
				0°	Dry condition	Damon Q	3.22 ± 0.92
Gracco <i>et al.</i> (2019) ^[21]	5°	Wet condition	In Ovation	1.24±0.12	3.35 ± 0.57	0.64 ± 0.06	0.79 ± 0.06
				0.95±0.09	1.01 ± 0.07	0.66 ± 0.13	0.94 ± 0.07
		Dry condition	Damon Q	1.45±0.17	1.75 ± 0.11	0.91 ± 0.19	1.13 ± 0.16
				1.27±0.18	9.25 ± 4.01	0.94 ± 0.11	1.19 ± 0.14
		Wet condition	Damon Q	1.43±0.06	7.96 ± 0.59	1.06 ± 0.07	1.06 ± 0.13
				1.87±0.10	1.33 ± 0.10	1.16 ± 0.07	1.27 ± 0.18
			In Ovation	2.52±0.09	4.06 ± 0.45	1.46 ± 0.13	2.35 ± 0.19

WCON-BCON (conventional S. S wire and bracket) WCON-BDLC (conventional S. S wire and DLC coated bracket) WDLB-BCON (DLC coated S. S wire and conventional bracket) WDLB-BDLC (DLC coated S. S wire and bracket), BTUC-1 (beta titanium uncoated) BTUC-2 (beta titanium TiAIN coated) BTUC-3 (beta titanium WC/C coated)

coating $[2.90 \pm 0.141$ (uncoated) 1.612 ± 0.029 (TiAlN coated) 1.56 ± 0.054 (WC/C coated)].

Risk of bias in individual studies

Risk of bias assessment was evaluated under 10 specific domains. Table 4 explains risk of bias assessment in individual studies. Most of the studies^[13,15-20] concluded at moderate risk of bias except Shah *et al.*,^[21] which was concluded at low risk and Samorodnitzky *et al.*,^[14] at high risk of bias. The items that most frequently received “no” in the analysis were: the randomization of specimens, loss of any specimen reported, and description of sample size calculation. In addition, all studies uniformly received “no information” entry under the description manufactures’ instruction followed, and the presence of an operator blinded to experimental condition.

Discussion

Significance of frictional force is apparent in sliding mechanics because this retarding factor reduces the amount of force employed by the fixed appliance for the desired tooth movement. Friction reduction would allow the application of a lower orthodontic force, with significant benefits, ranging from a lower risk of root resorption, to the best anchorage control, and reduction of the treatment time. Orthodontic research has been focussing in finding a solution to this problem with the support of material engineering. However, the most significant progress is being achieved with application of nanotechnology to the orthodontic archwires. In particular, coating orthodontic wires with nanoparticles is the best way to achieve better results in researches which were aimed at the reduction of friction. The inorganic fullerene-like tungsten disulphide (IF-WS₂) nanoparticles were described first in 1992.^[22] The size of these nanoparticles ranges from 20 to 200 nm depending on the tungsten oxide (WO₃) precursor size. Synthesis of fullerene-like WS₂ nanoparticles has allowed remarkable improvement of frictional behaviour and wear properties under different conditions.^[23] Solid lubricants of WS₂ nanoparticles penetrate into the interface between the rubbed surfaces which results in low friction and wear.

Three studies included in this systematic review used this fullerene-like nanoparticles with different combinations.^[13-15] 17--54% reduction of frictional resistance was obtained by coating the wire with nickel-phosphorous electroless films impregnated with inorganic fullerene-like nanoparticles of tungsten disulfide (IF-WS₂). The results obtained were in agreement with the study which showed that electroless plating of Ni-P and IF-WS₂ of a carbon steel substrate displayed excellent friction and wear properties due to their unique fullerene-like structure.^[24] Tribology data obtained from the cobalt and IF-WS₂ coated NiTi wires

Table 4: Risk of bias assessment

Study	Randomization of specimens	Prior sample size calculation	Similar size specimens	Manufactures’ instruction followed	Intervention defined	Control groups defined	statistical analysis considered	Blinding of observer	Loss of any specimen reported	All possible outcome reported	Overall risk of bias assessment
Redlich <i>et al.</i> (2008) ^[13]	No	No	Unclear	NI	Yes	Yes	Yes	NI	No	Yes	Moderate
Samorodnitzky <i>et al.</i> (2009) ^[14]	No	No	Unclear	NI	Yes	Yes	No	NI	No	No	High
Muguruma <i>et al.</i> (2011) ^[15]	No	No	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Moderate
Krishnan <i>et al.</i> (2012) ^[16]	No	No	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Moderate
Kang <i>et al.</i> (2015) ^[17]	No	No	Yes	NI	Yes	Unclear	Yes	NI	No	Yes	Moderate
Zhang <i>et al.</i> (2016) ^[18]	No	No	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Moderate
Behroozian <i>et al.</i> (2016) ^[19]	No	No	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Moderate
Shah <i>et al.</i> (2018) ^[20]	No	Yes	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Low
Gracco <i>et al.</i> (2019) ^[21]	No	No	Yes	NI	Yes	Yes	Yes	NI	No	Yes	Moderate

No- not taken into consideration/insufficient information; Yes- sufficient information provided regarding the specified domain; NI- no information provided regarding the specific domain

demonstrated 22–34% reduction of frictional forces.^[14] Both the studies showed that a substantial reduction in the frictional force was recorded at the highest angle and these findings were consistent with previous studies.^[25,26] Reason behind this is when the angle increases, load at the edges of the slot increases, causing a higher friction level on the uncoated wire. At this point, coated wires exfoliate some of the nanoparticles resulting in lubrication of the sliding. Models suggested by Rapoport *et al.*^[23] and Cash A *et al.*^[27] explains the mechanism by which there is an achievement of reduced friction, Corroboration with the results obtained with the previous studies, Gracco *et al.*^[15] also observed that improvements in terms of friction were obtained with coatings incorporating MoS₂ and WS₂. Friction reduction is primarily due to the “buffer” like action carried out by the nanoparticles, which flow between the surfaces, maintaining their shape. In high load conditions, nanoparticles induce the formation of a deposit at the level of surface roughness, reducing the direct contact between the asperities and minimizing wear.

Recently, DLC coating is becoming increasingly important in orthodontic applications owing to its superior properties.^[28,29] These nanoparticles are expected to offer the potential of greatly improving frictional properties. Muguruma *et al.*^[16] have investigated the effect of DLC coating on the static frictional force of stainless steel and nickel titanium orthodontic archwires and found that DLC coating process reduced the frictional force under dry conditions. In this study, although the stainless steel wires showed smoother and harder surface characteristics than the nickel–titanium wire, the stainless steel wires had greater frictional forces than the nickel–titanium wires. The stainless steel archwires had wider cross-sectional dimensions and a higher value of the elastic modulus than the nickel–titanium wires, and this should have affected binding and notching. Kang *et al.*^[18] investigated the frictional behaviour of DLC-coated archwires and brackets by using self-developed tester in ambient air of artificial saliva. Conventional archwires and brackets without DLC coating had lower friction coefficients in artificial saliva than they were in ambient air. However, no correlation was found between applied environment and friction coefficient for the DLC-coated wires. The results confirm that the saliva medium tends to decrease the friction coefficient for the uncoated wires, by favouring the lubrication of the interface, but it does not affect the friction coefficient for the DLC-coated wires.^[30,31] Nevertheless, the DLC-coated and uncoated brackets showed no significant differences in the friction coefficient. This is not consistent with previous report of Muguruma *et al.*,^[32] as they showed that DLC-coated brackets showed significantly less kinetic frictional force than as-received brackets. In addition

to the improvement in frictional characteristics of DLC-coated archwires Zhang *et al.*^[17] found that after surface modification, microhardness of the DLC-coated archwires was increased 1.46 times compared with the control group and the nanoindentation test revealed that the elastic modulus of the DLC-coated wires obtained was significantly lower than that of the control wires. DLC-coated wires with a lower elastic modulus might show superior flexibility, which is a desirable characteristic of an orthodontic wire. DLC films are harder than most metallic materials with hardness values ranging from 6 GPa to 20 GPa depending on the deposition conditions.^[33,34]

One study^[19] evaluated the effect of ZnO nanoparticles coating on stainless steel archwires and porcelain brackets and presented that ZnO nanoparticles coating on porcelain brackets was more effective than coating on wire. This can be contributed to the surface properties of porcelain brackets.^[35] Since the high surface roughness of porcelain brackets is an important factor in the determination of frictional forces, modification of such surface may have potential to reduce the sliding friction and covering the wire with ZnO nanoparticles did not result in major changes in frictional forces and these results were consistent with study conducted by Kachoei *et al.*^[36]

Shah *et al.*^[21] quantitatively assessed the effect of silver coating on frictional resistance of SS wires and suggested that there was no statistically significant difference in frictional resistance between silver coated and uncoated wires. But SS wires showed significantly less frictional force in silver coated larger dimension wire (0.019”×0.025”) and this can be due to the difference in the play of smaller (0.017”×0.025”) and larger dimension (0.019”×0.025”) wires.^[33] Krishnan *et al.*,^[20] evaluated frictional properties, behavior and surface analysis, mechanical testing, microstructure and elemental analysis of TiAlN and WC/C coatings on titanium-molybdenum (TMA) orthodontic archwires. This study clearly indicated the superior nature of WC/C coated orthodontic archwires over uncoated and TiAlN coated archwires, exhibiting reduced frictional forces to sliding mechanics.

Two studies^[15,18] compared the frictional behaviour of self-ligating brackets in combination with coated wires. The self-ligating brackets has basic advantages, as they eliminate the need of certain utilities or materials such as elastomeric modules, along with the process or tools associated with their application. In addition, it has been proposed that due to bracket–wire engagement, light forces and reduced friction can be attained with a desirable outcome on the rate of orthodontic tooth movement. Both the study concluded that self-ligating

brackets produced significantly less frictional forces than conventional brackets. Coating stability after friction testing was evaluated by SEM and XRD by all the studies except Shah *et al.*,^[21] and only one study^[13] evaluated the coating stability by manual bending test. All the included studies clearly demonstrated the coating method used to deposit the nanoparticles over archwires. Coating methods are specific for the chemical nature of the particular nanoparticles. For fullerene-like nanoparticles, electro-less deposition were used by two studies^[13,14] and electro-deposition by one study.^[15] Compared to electroless deposition, which is frequently used electrodeposition has made the coating application more controllable and manageable and this is in agreement with the similar trails carried out by other studies. PBIID (Plasma-based ion implantation/ deposition) and MCECR (Mirror- confinement- type electron cyclotron resonance) plasma sputtering was used by two studies^[16,18] and produced successful results while PVD (Physical vapour deposition) were used by few other studies.^[17,20,21]

Future research and recommendations

All the 9 studies were *in vitro* experimental study; there are controversies among different investigators regarding the effects of the intraoral lubrication. Few studies claimed that wet conditions were ineffective on several materials.^[37,38] Only two studies^[15,18] compared the frictional behaviour of the coated wires in both dry and wet conditions, however the results obtained by them were extremely heterogeneous with other. According to the results and to the limited evidence provided by the literature further investigations are needed to understand the behaviour of the coated wires in a condition simulating oral environment. The use of coated orthodontic wires in routine orthodontic practice can be implemented only after *in vivo* human clinical trials. Since few studies have been done to evaluate other physical/mechanical properties, further studies are required to explore these properties. Only two of the nine studies investigated the effect of nanoparticle coating on brackets in frictional resistance at bracket wire interface,^[18,19] results obtained from these studies were inconclusive and future researches are recommended to strengthen the evidence.

Conclusion

1. Null hypothesis has been rejected according to our systematic review, and it can be concluded that overall coating of orthodontic archwires has a positive effect in terms of frictional resistance at bracket-wire interface under specified in-vitro conditions. Moreover, it is recommended that coated orthodontic wires in routine orthodontic practice can be used only after *in vivo* human clinical trials.

2. Most of the studies were conducted over stainless steel arch wires and while comparing the frictional behaviour of coated stainless steel and other coated wires the former showed better performance in terms of frictional resistance after coating.
3. Many methods have been used for coating of orthodontic wires producing reliable coating stability. PBIID (plasma-based ion implantation and deposition) and electrodeposition method can be successfully used to create a surface layer with consistent repeatability.
4. During the reviewing process it is found that diamond like carbon (DLC) and fullerene like tungsten disulfide (IF-WS₂) nanoparticles significantly reduce the friction of orthodontic arch wires up to 50% under different experimental conditions.
5. Further studies are necessary to strengthen the evidence regarding effect of coated brackets on frictional properties at bracket-wire interface and effect of overall coating on other mechanical properties.

Abbreviations

SS (stainless steel), NiTi (nickel titanium), DLC (diamond like carbon), TiAlN (titanium aluminium nitride), WC/C (tungsten carbide), IF-WS₂ (fullerene like tungsten disulfide), ZnO (zinc oxide), PBIID (Plasma- based ion implantation/deposition), MCECR (Mirror- confinement- type electron cyclotron resonance), PVD (Physical vapour deposition), SEM (scanning electron microscope), XRD (X-ray diffractometry), Gpa (gigapascals), Hv (Vickers hardness).

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Conflicts of interest

There are no conflicts of interest.

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