

Effects of intraoral aging of arch-wires on frictional forces: An *ex vivo* study

Avinash Kumar, Arifa Khanam and Hajra Ghafoor

ABSTRACT

Introduction: Archwires act as gears to move teeth with light, continuous forces. However, the intraoral use of orthodontic archwires is liable to surface deposits which alter the mechanical properties of archwires, causing an increase in the friction coefficient.

Objectives: To evaluate the surface changes of the stainless steel archwires after 6 weeks of intraoral use and its influence on frictional resistance during sliding mechanics.

Materials and Methods: As-received rectangular 0.019" × 0.025" stainless steel orthodontic archwires (control) were compared with the archwires retrieved after the final phase of leveling and alignment stage of orthodontic treatment collected after 6 weeks of intraoral exposure (test samples) from 10 patients undergoing treatment. The control and test samples were used to evaluate surface debris using Scanning Electron Microscopy, surface roughness was assessed using Atomic Force Microscope and frictional forces were measured using Instron Universal Testing Machine in the buccal inter-bracket region that slides through the molar tube for space closure. Unpaired *t*-test and Pearson correlation tests were used for statistical analysis ($P < 0.05$ level of significance).

Results: Significant increase was observed in the level of debris ($P = 0.0001$), surface roughness ($P = 0.0001$), and friction resistance ($P = 0.001$) of orthodontic archwires after their intraoral exposure. Significant positive correlations ($P < 0.05$) were also observed between these three variables.

Conclusion: Stainless steel test archwires showed a significant increase in the degree of debris and surface roughness, increasing the frictional forces between the archwire-bracket interfaces which would considerably reduce the normal orthodontic forces. Thus, continuing the same archwire after levelling and alignment for space closure is not recommended.

Key words: Archwires, friction, intraoral aging, surface debris, surface roughness

INTRODUCTION

In contemporary orthodontics, many practitioners use sliding mechanics for both aligning irregular teeth and closing extraction spaces. Tooth movement associated with sliding mechanics

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involves a dynamic relationship among the archwires, brackets and ligation type in the oral environment.^[1] Archwires act as gears to move teeth with light continuous forces. The wires behave elastically to these forces over a period of weeks to months. However, the intraoral use of orthodontic archwires is liable to surface deposits and thus corrosion. These factors affect the surface topography and mechanical properties of the archwires causing an increase in the friction coefficient.

A coefficient of friction is a value that shows the relationship between the force of friction between two objects and the normal force between the objects. Friction develops when one

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moving object (archwire) contacts another (bracket slot/ligature wire) tangentially, resisting movement; thus, reducing the forces applied by treatment appliances. Further, to add this, is the oral environment wherein the orthodontic arch wires are clinically used. Surface films become the most powerful modifiers of friction; generally, friction tends to be high for very rough or very smooth surfaces. Very smooth surfaces make possible relatively large areas of adhesion that tend to grow during sliding, and very rough surfaces cause high friction because of the contact and interlocking of peaks and valley on their surface.^[2] The biological variables causing increased friction include the presence of saliva, acquired pellicles, corrosion and plaque which present as an adhesive interference by increased surface tension in the archwires. Friction is considered to reduce the rate of physiological forces applied to move teeth, as these forces are consumed to overcome the surface roughness of the intraoral archwires. Thus, an analysis of the surface characteristics of archwire material after intraoral use could be related to the frictional resistance offered by the material.^[3]

Of the four major alloys used stainless steel, cobalt-chromium, nickel titanium (NiTi) and beta-titanium, stainless steel is the most popular and commonly used archwire in fixed mechanotherapy. The role of the orthodontic wire alloys in frictional characteristics of sliding mechanics has been extensively studied, and it has been reported that stainless steel offers the least frictional resistance when compared to the other orthodontic alloys.^[4] However, the increased cross-section of the stainless steel wire used during final leveling and alignment phase before retraction exhibits increased archwire stiffness which becomes the controlling factor for frictional resistance.^[5]

Further, there are the popular stainless steel ligature ties or the use of elastic modules to engage the archwire into the bracket slot. Stainless steel ligatures have been suggested to create less friction when compared with elastic ligatures. Also, the passively tied steel ligatures produce lesser frictional resistance than the actively tied stainless steel ligature wires.^[6-8]

The sliding technique used to accomplish orthodontic treatment consists of the sliding of the rectangular archwires in the bracket slot of premolar teeth and in the buccal tube of molar teeth, allowing the remaining spaces of the extracted teeth to be closed. The main advantage of the straight wire system is the simplicity of the system because after the levelling phase all bracket slots lie in the same plane. This configuration permits sliding of teeth easier. Also, during the sliding biomechanics, the MBT system advocates using a pre-adjusted appliance with a 0.022"×0.028" slot, 0.019"×0.025" rectangular steel archwires and 0.010" steel ligatures associated with modules for the retraction system. Surface morphological changes that occur due to intraoral use of the orthodontic archwires increases orthodontic frictional forces between the archwire/bracket interfaces due to increase in the surface roughness. It results in an inappropriate force distribution on orthodontic appliances

and, consequently, the effectiveness of arch guided tooth movement decreases.^[9]

The science of dental materials has gathered more information regarding the mechanical properties (surface roughness, frictional resistance, etc.) of as-received orthodontic archwires than to the changes produced in them after intraoral exposure. Also, the surface roughness and frictional resistance of the archwires were evaluated by simulating the appliance design and its immersion into the *in-vitro* conditions which vary significantly from the intraoral environment. Thus, it is necessary to examine the surface changes produced by the oral environment in the mechanical properties of stainless steel archwires during routine orthodontic tooth movement.

The aim of this study is to evaluate the surface roughness and frictional resistance offered by the stainless steel archwires after 6 weeks of intraoral use.

MATERIALS AND METHODS

This is a clinical *ex-vivo* study conducted in the department of orthodontics and Dentofacial Orthopedics; approved by the ethical committee. Ten patients undergoing orthodontic treatment are selected for the study. Signed consent is sought by the subjects explaining to them the nature and purpose of this study. Materials used: Preformed archwires: Stainless steel 0.019" × 0.025" (3M Unitek, St Paul, Minnesota, USA) 20 upper and 20 lower archwires. Brackets: 0.022" × 0.028" slot, metal brackets (American Orthodontics: 3524 Washington Avenue). Ligatures: 0.010" stainless steel ligature wires (Leone S.p.A., Firenze FI, Italy).

The primary inclusion criterion for these patients is the need for 1st premolar extraction as a treatment protocol and patients with good oral hygiene are selected. These patients on the verge of completion of their 1st stage (Leveling and Alignment) of fixed mechanotherapy are put on 0.019" × 0.025" stainless steel upper and lower archwires.

Castroviejo caliper (for precise measurements) is used to measure: The extraction site and the length of the archwire between: (a) Distal aspect of canine bracket to mesial of premolar bracket, (b) distal of premolar to mesial of molar tube (our area of interest), (c) mesial of molar tube to the terminal end of the archwire, in all the four quadrants [Figure 1].

The wire segment between the premolar bracket and molar tube is considered important for our study because this buccal inter-bracket wire segment is more prone to exposure to saliva, food and sliding of the archwire through the molar tube during space closure (stage II of treatment). These final archwires, 0.019" × 0.025" stainless steel, of the stage I (leveling and alignment phase of treatment) are left passive intra-orally for about 6 weeks for the expression of torque. After the completion of this duration of 6 weeks, these 0.019" × 0.025" stainless

steel archwires are retrieved from patient's mouth. These 20 archwires, the upper and lower archwires for 10 patients, are then segmented into hemi-arch wires at the incisor area and stored.

The hemi-arch wires were stored in four closed containers 10 each, with a layer of modelling wax onto which the wires were set upright. The tips of the wires that maintained contact with the wax were not used in the examinations. All examinations are performed within 48 hrs of removal of the archwires from oral environment.

The 40 hemi-arched wires are then divided into 2 test groups – T1 and T2: T1: Two hemi-arch test wire segments (upper and lower) for the right side of each patient, T2: Two hemi-arch test wire segments (upper and lower) for the left side of each patient i.e., 20 hemi-arch wire segments in each group. C: The 20 as-received stainless steel archwires that serve as control are grouped as: C1 and C2 with 10 control archwires in each group.

T1 test archwires, specifically the buccal segments of the archwire between 2nd premolar bracket and molar tube are evaluated for the frictional resistance with the help of Instron Universal Testing Machine (Instron UTM) in comparison with the C1 control archwires and, the same part of the segment of archwire is examined for the surface debris using Scanning Electron Microscopy (SEM) and compared with the surface characteristics of control archwires.

T2 test and C2 control archwires are used to evaluate the three dimensional surface characteristics and to quantify the surface roughness of each archwire with the help of Atomic Force Microscope [AFM].

Evaluation of Frictional Forces

Two rectangular acrylic plates (area = 2.8 cm × 5.5 cm and thickness = 0.4 cm) were obtained and two stainless steel pre-adjusted edgewise brackets (0.022" × 0.028")

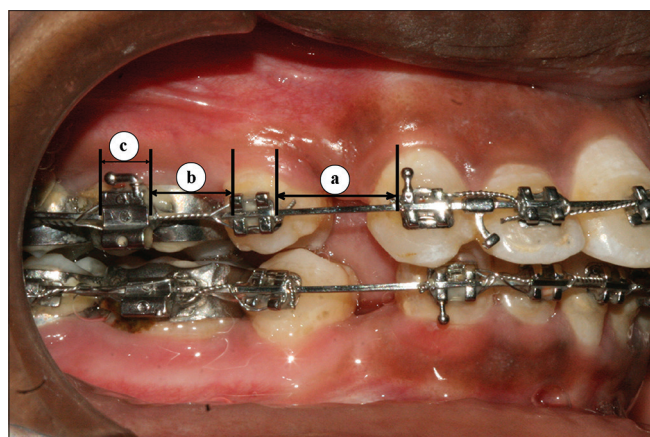


Figure 1: Precise measurement of buccal inter-bracket archwire segment for the study: (a) Distal aspect of canine bracket to mesial of premolar bracket, (b) distal of premolar to mesial of molar tube and (c) mesial of molar tube to the terminal end of the archwire

were bonded on each plate. For this, a thick stainless steel archwire (0.021" × 0.025") was placed in the bracket slot, providing a full filling for the bracket alignment, and was removed after the composite had cured. The two brackets were bonded at a distance of 4 mm.

For the friction test, each test/control wire segment had one-end bent; the part of the wire segment that lied distal to canine was bent. The wire was then tied to the brackets using a 0.009" diameter stainless steel ligature wires; special care was taken so that the part of the wire segment [Figure 1b] that lied in between the premolar bracket and molar tube intra-orally was now at the free end to slide through the bracket for evaluation of frictional forces.

The plates of acrylic containing the wire segments were fixed in the Instron-UTM (INSTRON 5967) and positioned between the grips perpendicular to the ground, such that the acrylic plate containing the bent wire end was set at the upper grip [Figure 2]. The machine was connected to a computer which contained the 'Blue Hill' software program (Bluehill® Software) to record the measurements. The 0.019" × 0.025" stainless steel wire segment's dimensions were fed in millimetres as 0.48mm (thickness) and 0.64mm (width); the plates to be moved at the rate of 0.5mm/min for 10 minutes to cover a distance of 5mm. The upper and the lower grips were tightened to hold the acrylic plates containing the wire segments, and the software programme was started which enabled the machine to slide the upper grip at a speed of 0.5 mm/min for a distance of 5mm. This moved the wire segment through the bracket, and the slightest changes in the force levels to pull the wire through the bracket were recorded. These measurements were recorded on an x and y axes-graph; the x axis representing the distance the wire moves through the bracket whereas the y axis denotes the frictional forces between the wire and the bracket slot.

The test model was the same for all friction tests, so only the wire segments and stainless steel ligatures were changed. After

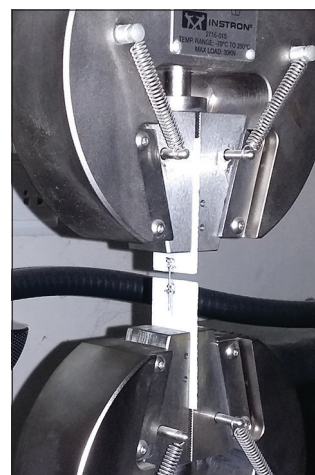


Figure 2: Test setup with acrylic plate model in Instron Universal Testing Machine for analysis of frictional resistance

each friction test, the brackets bonded to the plate were cleaned with gauze soaked in alcohol (96%) to eliminate possible debris from the previous wire.

C1 control wires and T1 test samples were evaluated for kinetic frictional forces which were measured in Newton (N), and the mean frictional force was calculated for every specimen.

Evaluation of the Surface Characteristics

Surface characteristics of each of the test wire segments were studied with the help of a SEM (Gemini ZEISS Supra 40). The upper tip of each segment of the wire was fixed on a glass slide, and the area of interest i.e., the part of the wire between mesial of molar tube and distal of premolar bracket was marked and determined previously in order to standardize the reading. About a centimeter long specimen of our area of interest [Figure 1b] on the wire segment was mounted on studs containing the carbon plates, which were later placed in the vacuum chamber of the SEM. The accelerating voltage (20kv), angle of fit, and the aperture was adjusted to optimize the quality of the micrograph. The surface was scanned and viewed on the monitor at different magnifications and representative micrographs ($\times 200$, $\times 500$ and $\times 1000$) of each sample and control archwires were obtained [Figure 3].

Assessment of the amount of debris on the surface of the wires was performed by a single examiner on the micrograph images obtained at $\times 200$ magnifications. This magnification was selected because it allows for a greater surface area

to be covered on the wire. The following scores were used, according to previous published method:^[10] 0 = total absence of debris; 1 = some debris, involving less than one-fourth of the image analyzed; 2 = moderate presence of debris involving one-fourth to three-fourths of the image; 3 = presence of a large amount of debris involving more than three-fourths of the image examined [Figure 4]. T1 test samples were evaluated and scored for the surface debris that has occurred on their intraoral exposure in comparison with the surface of the C1 control archwires.

Surface Roughness

Test sample group T2 and control C2 wires were examined for surface roughness and three-dimensional images were obtained using AFM (NANOSURF Easy Scan). The samples were attached to a metal holder using rapid-drying cyanoacrylate glue, and then, for each specimen, three areas ($10 \mu\text{m} \times 10 \mu\text{m}$) of the surface were randomly selected and were observed with an AFM probe operating in contact mode under ambient conditions. Three-dimensional images (300×300 lines) were processed using 'Gwyddion software 2.9' (Czech Metrology Institute), and average roughness (Ra), mean square roughness (Rms), and maximum value height (Mh) were recorded. The Ra and Rms represent the arithmetical mean of the absolute values and the root mean square value of the scanned surface profile, respectively; Mh is the maximum height of a profile peak. Ra is chosen to characterize the topography of orthodontic wires.

Statistical Appraisal

Statistical analysis was carried to determine the significant difference between the control (C1, C2) and test (T1, T2) archwires for surface changes and frictional resistance. Unpaired student's *t*-test was used to evaluate the significant difference in the surface debris scoring and friction resistance of the test archwires in comparison with the control groups of archwires. Also, the statistical significant difference between

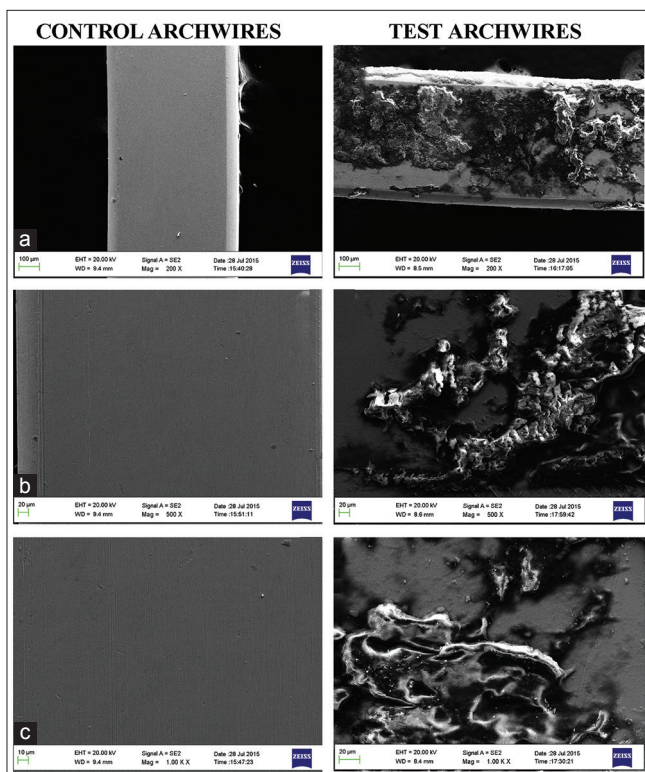


Figure 3: Comparison of scanning electron micrographs of control and test archwires at (a) $\times 200$, (b) $\times 500$ and (c) $\times 1000$

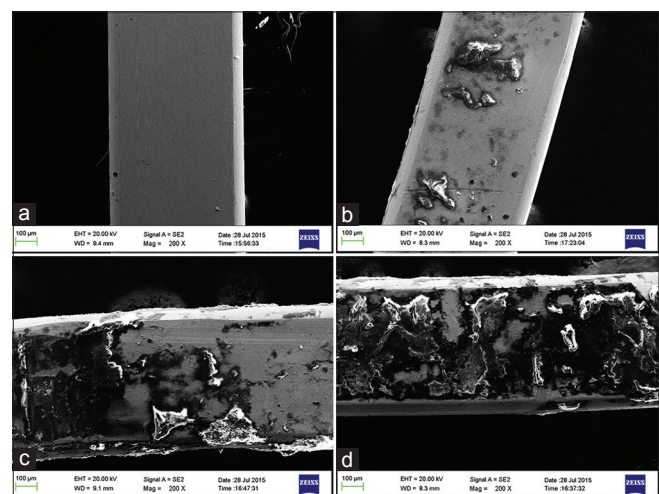


Figure 4: Scoring for the Scanning electron microscopic images according to the amount of debris at $\times 200$: (a) Score 0: no debris, (b) 1 - $\leq 25\%$ debris; (c) 2-25-75% of debris and (d) 3 - $\geq 75\%$ of debris

surface Ra and friction resistance of the test and control archwires was assessed using unpaired student's *t*-test. Further, the kind of relationship between surface changes and frictional forces of the test archwires was ascertained using Karl Pearson's correlation.

RESULTS

Analysis of Surface Characteristics

The examination of surface characteristics of control stainless steel arch-wires under SEM revealed smooth and regular surfaces. Analysis of debris on these wires showed a complete absence of debris (zero score) for all wire segments at $\times 200$ magnification. However, the SEM micrographs of retrieved test arch-wires showed a marked increase in the degree of debris with an average score of 2.15 (moderate debris) at $\times 200$ magnification. Thus, unpaired *t*-test reported a highly significant difference between the surface characteristics of control arch-wires and the test arch-wires ($P = 0.0001$) [Table 1 and Figure 4].

Analysis of Surface Roughness

AFM analysis provides quantitative evaluation of the surface roughness in terms of Ra. The roughness analysis showed a highly significant difference between the surface roughness average of test arch-wires and control arch-wires ($P = 0.0001$) [Table 1 and Figure 5].

Analysis of Frictional Resistance

There was a significant increase in the frictional forces of the test arch-wires ($P = 0.0001$) when compared with the control arch-wires, with an average increase of 2.7N, corresponding to a 39.7% increase in the friction level [Table 1].

Correlation between Frictional Force, Amount of Debris, and Roughness

Spearman correlation analysis showed a highly significant association between kinetic friction and the degree of debris measured at $\times 200$ magnification ($r = 0.82$; $P = 0.0001$); also, there was a significant correlation between surface roughness and kinetic friction ($r = 0.73$; $P = 0.0001$) of the test arch-wires indicating that as the amount of debris and roughness on the arch-wires increases during their intraoral use, greater becomes the amount of frictional resistance during orthodontic tooth movement [Table 2 and Figure 6].

A positive correlation between surface debris and roughness was also determined ($r = 0.69$; $P = 0.001$), to ascertain the surface changes on the test archwires after 6 weeks which cause a considerable increase in the frictional forces [Table 2 and Figure 6].

DISCUSSION

Stainless steel archwires are the most popular archwires used during the course of orthodontic treatment, attributed to its elastic modulus, low friction, formability and biocompatibility. The present study incorporated the clinical use of rectangular 0.019" \times 0.025" stainless steel archwires motivated by the fact that these wires remain passive in the intraoral environment for about 6 weeks for torque expression during the final phase of 1st stage (leveling and alignment) of orthodontic treatment. Also, they are very useful during mechanical sliding because of their lower coefficient of friction and lower surface roughness.^[4,11-13] Pre-adjusted edgewise stainless steel brackets were used in this study as they are commonly used in clinical practice, and the stainless steel archwires were engaged in brackets with the help of stainless steel ligatures which have poor

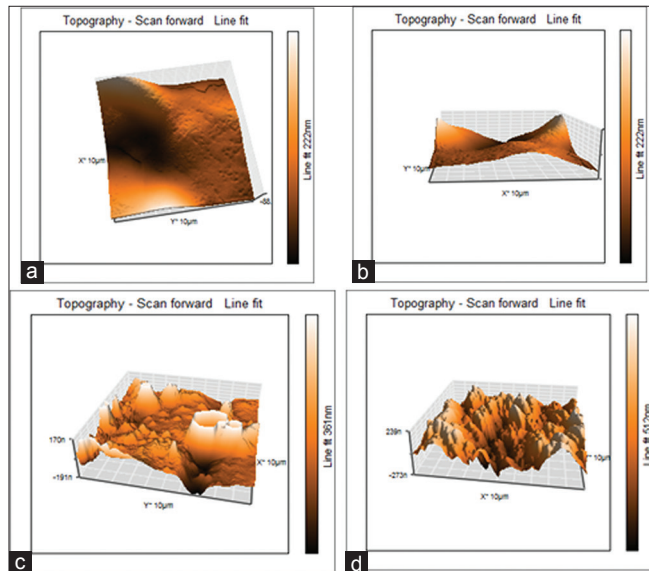


Figure 5: Three-dimensional images obtained by Atomic Force Microscopy: (a and b) Images of the control wires showing homogenous surfaces, (c and d) Images of test archwires showing peaks and elevations of the surface topography

Table 1: Descriptive statistics for debris, roughness, and friction and P values for comparisons of as-received stainless steel archwires and clinically used stainless steel archwires

Variable	As-received (control wires)		Clinically used (test wires)		P
	n	Mean/ SD/IQR media	n	Mean/ SD/IQR media	
Debris ($\times 200$)*	10	0	20	2.15/2 0.79/1	0.0001
Roughness (Ra)	10	19.45 0.68	20	125.87 49.8	0.0001
Friction	10	6.82 0.46	20	9.55 0.59	0.0001

*Debris at $\times 200$ are described by medians and IQRs as well; roughness and friction are described by means and SDs. IQR: Interquartile range, SD: Standard deviation

Table 2: Correlation coefficients (r) and P values for the variables examined

Variable	r	P
Friction-debris	0.82	0.0001
Friction-roughness	0.73	0.0001
Debris-roughness	0.69	0.001

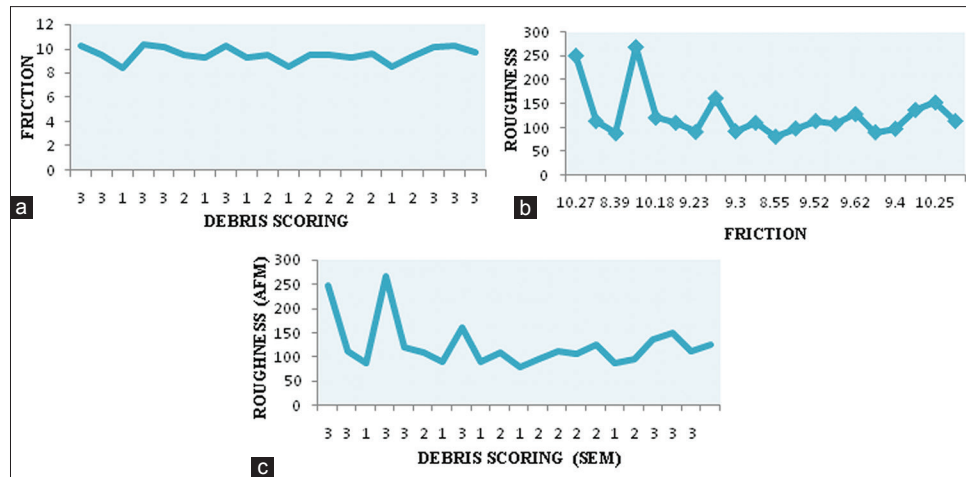


Figure 6: Scatter diagram suggesting positive correlation between (a) debris scoring and friction, (b) surface roughness and friction, which indicates that as the surface debris and roughness increases frictional resistance also increases and (c) Positive correlation between surface roughness and debris scoring indicates that the debris scores are high for increased surface roughness values

biohostability when compared to the elastomeric ligatures which also undergo force decay.^[7,14]

Friction is an unwelcome vector encountered in orthodontic treatment modalities and studied extensively in the literature.^[4,6,10,12,15-21] However, intraoral aging of the orthodontic archwires and their effects on frictional resistance put forth by many in-vivo studies discourages the prolonged use of orthodontic archwires.^[10,12,17,18,22] Stainless steel orthodontic archwires widely used in orthodontic treatment procedures are less probed than the NiTi wires. Our study evaluated the frictional resistance offered by the rectangular stainless steel orthodontic archwires when exposed to the intraoral environment for about 6 weeks during the final wire sequence (0.019" × 0.025") of leveling and alignment stage. Usually the same archwires are continued during the retraction stage of orthodontic treatment, the friction encountered in the archwire-bracket interface during this stage has the potential to reduce the orthodontic forces thus applied. Further, the region specifically analysed for frictional resistance was the inter-bracket distance between the 2nd premolar bracket and 1st molar tube where the archwire actually slides to bring about space closure. Comparison of the frictional forces between control and test archwire segments showed an average increase of 2.7N (39.7%) after 6 weeks of intraoral exposure. The values of the present study do not differ from those reported previously by Hain *et al.*^[7] who reported that between 12% and 60% of applied force in fixed appliances is lost to friction and Proffit^[23] agreed that approximately 50% of the force necessary to initiate tooth movement is required to overcome the retarding frictional force generated between the various components of a fixed appliance.^[24] Further, resistance to sliding of orthodontic appliances in the dry state may not correspond to actual friction in the oral environment. The reason being, intra-orally, saliva causes an increase in friction by promoting adhesive and lubricious behaviours.^[25]

Classically, friction between two surfaces is directly related to the features of opposing surfaces; like surface roughness.^[26]

In routine clinical practice, even visual inspection of the as-received stainless steel archwires shows smooth and homogenous surfaces, whereas the intra-orally used archwires exhibits surface changes. However, this intraoral aging of the archwires can be effectively examined by SEM on a micrometre scale, which gives us 2-dimensional images at different magnifications. Many studies using SEM micrographs have shown surface changes on the surface of the orthodontic archwires when subjected to *in-vitro* conditions.^[15,20,25,27-34] A few other studies provided critical information of the accumulation of debris and corrosive products on the surface of the intra orally used orthodontic archwires.^[10,12,18,22,35-39] Four in-vivo studies concentrated on stainless steel orthodontic archwires; of which, Edie *et al.*^[12] in 1981 used stainless steel archwires in comparison with NiTi wires where in it was shown that intraoral exposure increased the susceptibility of the wire surface to corrosion because of the increased surface roughness. One study used multi-loop edgewise archwires in 0.016" × 0.022" stainless steel orthodontic wires;^[38] another study reported standard 3M Unitek stainless steel archwires to be better than other company stainless steel orthodontic wires.^[23] Only one study by Marques *et al.*^[10] reported the use of 0.019" × 0.025" stainless steel orthodontic archwires confined to the buccal segment intra orally; however the archwire segment was passively inserted into the pre-adjusted edgewise brackets from first molar to first premolar.

The present study however, puts forth the surface changes on the stainless steel orthodontic archwires after 6 weeks of intraoral exposure in an active orthodontic treatment regimen. The final archwires (0.019" × 0.025" stainless steel archwires) of leveling and alignment stage are collected for the evaluation of surface changes and its effect on frictional forces. The

specific region of the buccal inter-bracket archwire segment used to analyze frictional resistance was scanned for surface debris. SEM revealed surface deposits on the archwires after intraoral exposure which was scored accordingly.^[10] A debris score of 0 was obtained for as-received wires, but the scores were significantly higher for clinically used archwires.

The surface roughness of the clinically used archwires was determined with the help of AFM which is a non-invasive technique and less-time consuming.^[40,41] Here, the surface roughness of the clinically used archwires was estimated using the hemi-archwire segment at three different areas randomly. This was to understand the average surface roughness values that increase post-intraoral use. Further, SEM debris scores and AFM surface roughness values showed a positive correlation, indicating that the surface roughness in general was moderately proportional to the debris on the surface of the buccal inter-bracket archwire segment. This could be due to the assessment of the surface debris by scanning electron microscope, after the mechanical interaction between the archwire and bracket during the friction test; whereas the hemi-archwire segment used for AFM analysis was not touched.

Correlation analyses showed significant positive correlations between the degree of debris on the archwire surface, surface roughness, and friction. It is important to consider that the correlation between friction and debris was more significant, than the correlation between friction and surface roughness. This could be attributed to the evaluation of the same region of the archwire segment for both friction and debris, whereas surface roughness of the hemi-archwire segment was measured separately. No data were found in the literature for such an area-specific assessment of the stainless steel archwires during the course of orthodontic treatment for surface changes and friction.

Clinical Significance

Decontamination of the archwires has shown to significantly reduce the surface roughness formed by debris and plaque accumulation, but at the same time increases the wire stiffness.^[30,41] Thus, continuing the stainless steel archwire after thorough cleaning of the archwires at every clinical appointment to remove plaque and debris from the archwire surface is not recommended. Using a newer archwire to prevent an increase in friction during mechanical sliding is thus considered desirable.

CONCLUSION

This study concludes that rectangular stainless steel archwires exposed to the intraoral environment for about 6 weeks during the final arch wire sequence of levelling and alignment stage for torque expression shows a significant increase in the amount of debris and surface roughness. The frictional resistance of the archwires also increased markedly after their intraoral exposure when compared to the as-received archwires.

This intraoral aging of the stainless steel orthodontic archwires contributing to the increased degree of debris and roughness on the archwire surface is correlated to the frictional resistance of the archwires, which implies that there would be an increase in friction between the bracket-archwire interfaces during the space closure stage of sliding mechanics.

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Nil.

Conflicts of Interest

There are no conflicts of interest.

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