The effect of surface treatment and clinical use on friction in NiTi orthodontic wires

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Summary *Objectives*: Since the low friction of NiTi wires allows a rapid and efficient orthodontic tooth movement, the aim of this research was to investigate the friction and surface roughness of different commercially available superelastic NiTi wires before and after clinical use. The surface of all of the wires had been pre-treated by the manufacturer.
Materials: Forty superelastic wires (Titanol Low Force, Titanol Low Force River Finish Gold, Neo Sentalloy, Neo Sentalloy Ionguard™) of diameter 0.016×0.022 in. were tested. The friction for each type of NiTi archwire ligated into a commercial stainless steel bracket was determined with a universal testing machine. Having ligated the wire into the bracket, it could then be moved forward and backwards along a fixed archwire whilst a torquing moment was applied. The surface roughness was investigated using a profilometric measuring device on defined areas of the wire. Statistical data analysis was conducted by means of the Wilcoxon test.
Results: The results showed that initially, the surface treated wires demonstrated significantly ($p < 0.01$) less friction than the non-treated wires. The surface roughness showed no significant difference between the treated and the non-treated surfaces of the wires. All 40 wires however showed a significant increase in friction and surface roughness during clinical use.
Significance: Whilst the Titanol Low Force River Finish Gold (Forestadent, Pforzheim, Germany) wires showed the least friction of all the samples and consequently should be more conservative on anchorage, the increase in friction of all the surface treated wires during orthodontic treatment almost cancels out this initial effect on friction. It is therefore recommended that surface treated NiTi orthodontic archwires should only be used once.
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Introduction

Today's treatment of choice for malocclusion are fixed orthodontic appliances. The clinician can

choose from a large variety of different bracket systems and also from a wide range of alloys from which to select an arch wire for straight wire mechanics. During orthodontic treatment, teeth move intermittently along the archwire undergoing phases of tipping followed by uprighting in addition to rotational movements. The archwire lies in and is in contact with the bracket slot which leads to problems with friction and wear of the archwire. The amount the arch wire is deformed is dependent on the applied force and elasticity of the wire [1,23]. Some of the applied force is used to overcome the friction between the two surfaces in contact, i.e. the bracket and archwire. If static friction occurs, movement of the tooth is inhibited until the tooth is uprighted by the elastically deformed superelastic wire; tooth movement then occurs as the friction is reduced as the tooth slides along the archwire. Uprighting of the tooth requires an applied force from the archwire which has also unwanted side effects on the adjacent teeth and can strain the anchorage. The force necessary to bring about orthodontic tooth movement must clearly overcome the friction as well as move the tooth. This applied force has a reactive force on the molars which moves them in a mesial direction. This is frequently not a desired clinical response and can be considered as anchorage loss. It is clear therefore that the development of materials with low coefficients of friction for straight wire mechanics are highly desirable because they can reduce the strain on anchorage.

Friction between the bracket and archwire can cause up to 50% loss of force [5,9,11,18,21]. As a result the desired tooth movement is slowed down or even inhibited. It is therefore desirable that orthodontic wires and brackets show the lowest possible friction coefficients. Numerous factors have an impact on friction and it is very difficult to isolate individual factors. Besides the alloy composition of the archwire [2,13], the wire size [2,13], the elasticity [1,17,19] and the surface structure including surface treatments also play an important role. Studies have shown that the surface characteristics influence both the friction and the biocompatibility of orthodontic arch wires in situ [4,6,11,14,16,20,21,23]. Plaque accumulation is affected by the surface roughness and this in turn affects the properties described above.

When describing friction in orthodontics we have to consider a system consisting of three variables which are relevant: the bracket as a friction counterpart, the wire as a friction solid and the surrounding medium. In the present study, the effect clinical use of the wires has on the frictional forces was analysed using a laboratory friction test system which measures the friction between the stainless steel surface of the bracket and a torqued NiTi arch wire in dry conditions. Measurements of the surface roughness were also carried out before and after use of the wires.

Superelastic NiTi wire shows a martensitic transformation between the austenite and the martensite phases during loading and unloading as well as during cooling and heating. This transformation leads to large amounts of reversible strain occurring either during heating (shape memory effect) or during loading (superelastic effect) [10]. In orthodontics both effects are important, although the key effect is the superelasticity, which produces reversible strains of up to 8% [23]. Understanding the physics of these effects is of importance for both fracture mechanics as well as friction and wear because the phase transformation in shape memory alloys dissipates large amounts of elastic energy. Consequently, NiTi shape memory alloys are known for being surprisingly resistant to wear despite their relatively low surface hardness. Also with respect to this study, it is important to appreciate that the implementation of conventional hardening mechanisms to increase the wear resistance such as dislocations, precipitations or particles in NiTinol is very limited. This is due to the fact that the functional properties of NiTinol are very sensitive to almost any of the aforementioned hardening mechanisms. Therefore, most mechanisms and treatments which may be applied to increase the hardness of NiTinol are typically related to a decrease of functional properties, such as the length of the lower pseudoelastic plateau, the transformation temperature of the alloy or the shape of the plateau.

Besides conventional mechanical polishing techniques there are other surface treatments which can be carried out during manufacturing such as ion implantation, a technique in which the metallic substrate is hardened by the implantation of high energy ions in a very thin surface layer. The increase in hardness is due to the mechanical stresses induced by the mismatch of the implanted ions in the crystal structure of the substrate [5].

The manufacturers claim that pre-treated wires reduce friction during orthodontic fixed appliance mechanics. The aim of this research was to investigate whether the friction of different commercially available superelastic NiTi wires was indeed constant before and after 4 weeks of clinical use and also whether there was any change in surface roughness and how this was related to any change in friction. The wires under investigation

had been exposed to one of the two surface treatments by the manufacturer:

– Conventional surface polishing of the wires;
– Wires treated with ion implantation.

Materials and methods

Four different commercially available NiTi wires with two different surface treatments were investigated. The rectangular wires were 0.016×0.022 in. in dimension. The following commercially available wires were included in the investigation:

- Titanol Low Force (Forestadent, Pforzheim, Germany), mechanical polish;
- Titanol Low Force River Finish Gold (Forestadent, Pforzheim, Germany), mechanical polish plus ion surface treatment;
- Neo Sentalloy F80 (GAC Int., NY, USA), mechanical polish;
- Neo Sentalloy F80 Ionguard™ (GAC Int., NY, USA), mechanical polish plus ion surface treatment.

The participants for the clinical study were 20 juvenile patients who were in the levelling phase of fixed orthodontic appliance therapy.

Friction tests

Elastic ligation (clear power chain, Ormco, CA, USA) was used for all friction tests in order to exclude any influence of different ligature systems on the results.

The initial friction was measured on 10 archwires of each product. This sample constituted the control group. They were not subsequently used in the patient's mouth since the friction test leaves scratch marks on the wire which leads to a change in the roughness measurements.

Friction was additionally measured after the archwire had been inserted into the patient's mouth for 4 weeks, which is equivalent to a normal interval between orthodontic appointments for a patient with fixed appliances. The testing equipment to measure the friction of the superelastic wires was the Universal test machine (Zwick 1425, Ulm, Germany) with a measuring speed of 20 mm/min and a pre-set torque of 5 N mm. The experimental apparatus is shown in Fig. 1. It was set up to simulate tooth movement during the levelling phase. To ascertain the friction coefficient, three test cycles were used. The Statistics program STATISTIKA V.97 (StatSoft, Tulsa, USA) was used for the statistical analysis of the results using the Mann Whitney U-Test for non-parametric data.
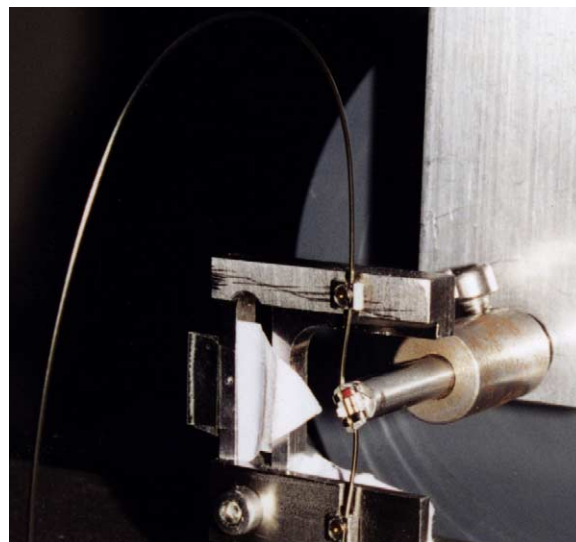

Figure 1 Experimental apparatus for friction measurements showing a torqued NiTi wire ligated into a bracket which was then integrated into the Zwick Universal Testing machine.

Surface roughness tests

The surface roughness measurements were carried out with a confocal laser scan microscope (LSM 410, Zeiss, Germany) [3] and a photo cell to record and measure dispersed laser light (Institute of Laser Technology, Ulm, Germany [4,8]). The light source was a 2 mW laser diode at 633 nm and the lens used had a focal length of $f = 100$ mm. The angle of incidence of the laser on the tested portion of the wire and the angle of reflection were 45°. The detector was located at a distance of 5 cm from the tested sample within a detection area of $\pm 10°$ of the angle of reflection. A measurement of the roughness parameters (R_q and R_z) were ascertained at five defined sites with a Hommel tester (T 2000, Hommel, VS-Schwenningen, Germany) [4]. This has an arm with a diamond tip TKL 100 (radius 5 μm) fitted at an angle of 90° and moves at a linear and constant speed ($v_t = 0.02$ mm/s). The measuring area was defined with notches from the middle of the archwire to the distal of the canines. After establishing the norm, roughness was measured at five points in a defined area. The results for the roughness parameter R_q can be calculated from the measured R_a values by the formula as:

$$R_a = \sqrt{\frac{2}{\pi}} R_q$$

The Wilcoxon test for paired samples was used to analyse the roughness parameters R_z and R_q.
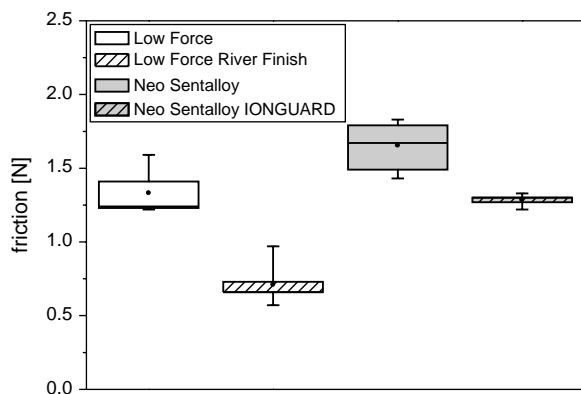
Figure 2 Friction force values before oral exposure ($n = 10$ per tested group).
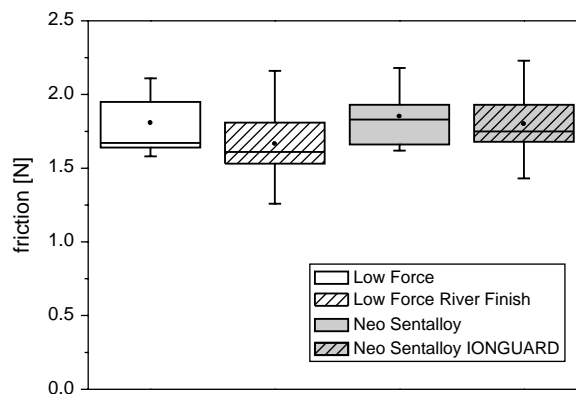

Figure 3 Friction force values after 4 weeks of oral exposure ($n = 10$ per tested group).

Results

Friction

From the data for the different archwires prior to clinical use, the Low Force River Finish Gold had the lowest friction with an average of 0.71 N (Fig. 2, Table 1). The friction values for the Titanol Low Force wire were initially clearly much higher. Neo Sentalloy Ionguard™ wires showed lower friction values in comparison with the standard Neo Sentalloy wire.

The reduction in friction for the 'River Finish Gold' surface treated wire was 46% when compared to the standard Titanol Low Force wire and 23% for the 'Ionguard™' wire when compared to the Neo Sentalloy wire (Table 1). These findings were statistically significant. After 4 weeks of clinical use in the mouth, all wires showed higher coefficients of friction (Fig. 3, Table 1). Titanol Low Force River Finish wires had the lowest average friction for the second evaluation. The Neo Sentalloy Ionguard™ had a higher friction value. However,

there was no statistical significance between the two wire types. The difference in friction values before and after clinical use was 134% for the Titanol Low Force River Finish Gold. The difference for the untreated Titanol Low Force wires was only 36%. The difference in the coefficient of friction between the brand new Neo Sentalloy wires and those that had been in the mouth for 4 weeks was only 10% which was statistically insignificant.

Roughness

The qualitative results for the initial tests showed a clearly visible macroscopic change in the surface structure of the individual, unused NiTi wires before and after oral exposure. Additional qualitative investigations with the scanning electron microscope confirmed this impression. In Fig. 4 we can see the surface topography of a new NiTi archwire. After 4 weeks of exposure to the oral environment, it can be clearly seen that there is an increase in surface roughness within the same measurement site. These findings were also confirmed with the laser scanning microscope. The results for the roughness parameters tested with the Hommel tester are shown in Figs. 5 and 6 and Table 2.

The surface roughness of newly manufactured Titanol Low Force and Titanol Low Force River Finish Gold wires are clearly lower than the Neo Sentalloy and Neo Sentalloy Ionguard™. The average roughness of Neo Sentalloy Ionguard™ was 2.7 times higher than the Titanol Low Force wires with an R_z value of 0.74 μm and was shown to be the roughest archwire (Fig. 5, Table 2).

After 4 weeks in the oral cavity, the wires were visibly rougher as confirmed by the scanning electron microscope (Fig. 6, Table 2). The roughest surface was found for the Neo Sentalloy wire with

Table 1 Result of the friction tests before ($T0$) and after ($T1$) clinical use.

NiTi wires	$T0$: $\bar{x}$ (SD)	$T1$: $\bar{x}$ (SD)	Difference: $\bar{x}$ (SD)	Significance
Low Force	1.33 (0.12)	1.8 (0.04)	0.47 (0.08)	**
Low Force River Finish	0.7 (0.16)	1.66 (0.12)	0.35 (0.04)	**
Neo Sentalloy	1.67 (0.2)	1.8 (0.26)	0.18 (0.06)	n.s.
Neo Sentalloy IONGUARD	1.28 (0.07)	1.8 (0.1)	0.52 (0.03)	**

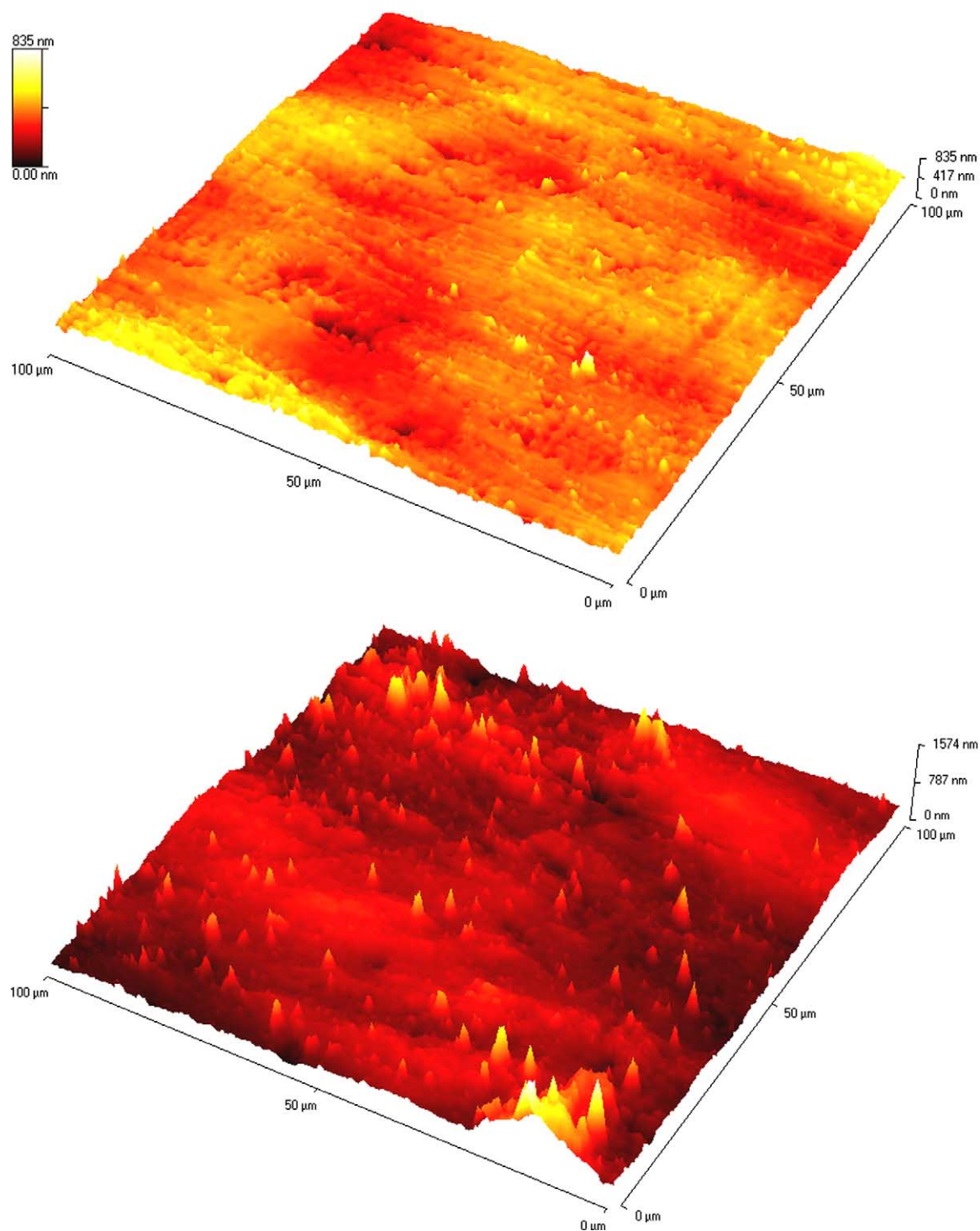$P \leq 0.05$, $P \leq 0.01$**, $P \leq 0.001$***.

Figure 4 3D Reconstruction of the surface topography of a NiTi wire before (upper view) and after (lower) 4 weeks of oral exposure in a scan field of $100 \times 100 \ \mu m^2$.

an R_z value of 1.2 μm. The roughness values for Titanol Low Force and Titanol Low Force River Finish Gold wires were doubled from 0.2 to 0.41 and 0.45 μm, respectively. The Titanol Low Force wires had lower roughness values than the Neo Sentalloy wires. The change in surface roughness for the Low Force wires was 105% and for the Titanol Low Force River Finish Gold wires was 119%. For the already rougher Neo Sentalloy wires, the roughness increased by 68%, whereas the wires which were surface treated, i.e. 'longuard™' deteriorated by only 53%. All four categories of wires on the second
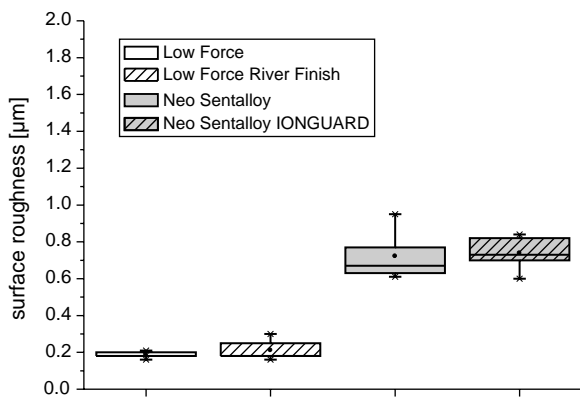
Figure 5 Surface roughness (R_z) before oral exposure ($n=10$ per tested group).

Table 2 Result of the surface roughness before ($T0$) and after ($T1$) clinical use.

NiTi wires	$T0 \bar{x}$ (SD)	$T1 \bar{x}$ (SD)	Difference $\bar{x}$ (SD)	Significance
Low force	0.19 (0.03)	0.41 (0.12)	0.22 (0.09)	***
low force river finish	0.21 (0.01)	0.46 (0.04)	0.25 (0.03)	***
Neo Sentalloy	0.72 (0.54)	1.21 (0.27)	0.49 (0.27)	***
Neo Sentalloy IONGUARD	0.74 (0.08)	1.13 (0.26)	0.39 (0.18)	***

$P \leq 0.05$, $P \leq 0.01**$, $P \leq 0.001***$.

investigation showed a change in the surface structure which adversely affected the roughness.

The correlation between friction and roughness

Following the exposure of the wires to the oral environment, no correlation was found between the increased surface friction and surface roughness (Fig. 7).

Discussion

Alignment of the teeth during levelling is affected by the friction of the archwires which is influenced by many factors such as the applied force, the surface characteristics of the wire, the properties of the material and the vertical dimension and width of the bracket and slot. The combined effects of these factors contribute to a complex effect on friction.

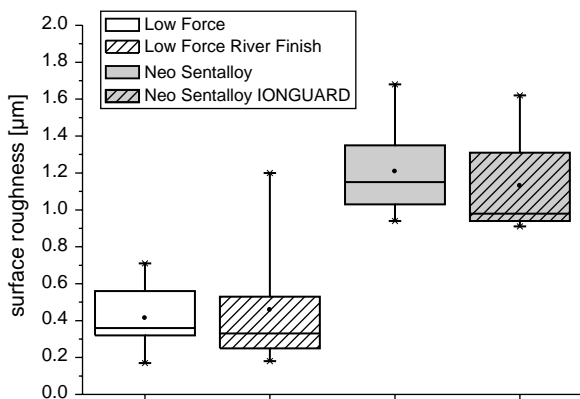Simulation of tooth movement is difficult because the resistance centre of the tooth during tooth movement is affected by additional factors such as the bone density, root conformation and length and the occlusion. The method used to simulate tooth movement and to measure friction has previously been described in the literature [5,12,13,22] and has been well tested.

This study has shown clearly that there are differences in the frictional behavior of NiTi wires. NiTi wires which have not been used in the mouth show a frictional force of between 0.7 and 1.7 N. Tooth movement undertaken with straight wire mechanics requires low frictional forces to reduce anchorage requirements, otherwise the use of headgear is needed to supplement the anchorage. From the literature, measurement of friction has mainly been confined to the comparison of NiTi, steel and TMA wires. There is very little information in the literature on the comparison of different NiTi wires and this makes comparison of our work with other research limited. Measurements from Ireland et al. [12] show values of 2.5 N. Our measurements showed clearly lower values for all the NiTi wires
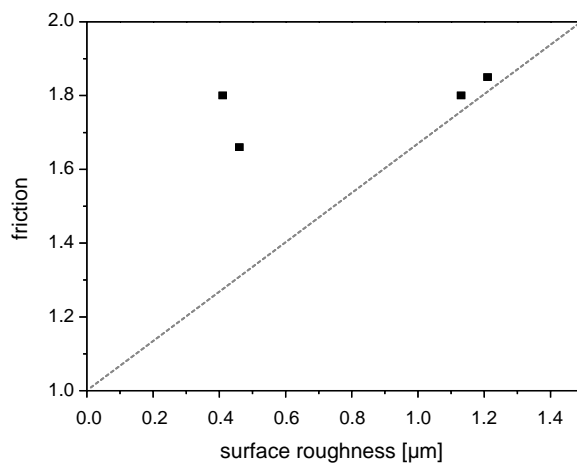

Figure 6 Surface roughness (R_z) after 4 weeks of oral exposure ($n=10$ per tested group).

Figure 7 Correlation between roughness and friction.

which was comparable with the friction values for steel wires of 1.5 N [12,9]. This is probably due to better manufacturing techniques and the development by the manufacturers of wires with lower frictional properties. As a result, today we can use NiTi wires almost exclusively in our clinical practice.

Although friction is multifactorial as described above, we have clearly shown from our results that the surface treatment of wires does improve sliding of the bracket along the archwire. At best, the surface treatment can reduce the friction by 46% which is confirmed in the literature. Literature findings also confirm that the frictional properties of archwires were improved if a surface treatment was applied, e.g. Teflon, polyethylene or ion implantation. The best result was found for the Teflon coated wires [11]. This was also confirmed by Burstone et al. [5]. The research from Burstone and Frazin-Nia [5] showed a significantly lower value for friction for the coloured TMA wire treated with ion implantation in comparison with untreated TMA and steel wires. The so-called 'Honeydew' TMA archwire treated with ion implantation showed a lower coefficient of friction than a steel archwire of the same dimension, which supports our findings. These values only apply to new unused wires. In contrast, Cobb et al. [7] and Kula et al. [15] reported that there was no significant difference in the effect of ion implanted TMA archwires on the rate of orthodontic space closure and tooth movement. This is important to stress because the positive effect of ion implantation on friction was lost in our study when the wires were exposed to the oral environment for 4 weeks, a normal interval for appointments in fixed appliance cases. Further studies are required to establish whether frictional benefits would be improved if the ion implanted wire remained for a shorter period in the mouth during the levelling phase. A firm conclusion cannot be drawn from only two measured time intervals, i.e. before and after 4 weeks of use. Thus, the following questions remain open and should be addressed with further research:

- How quickly does the frictional force increase once the wire is inserted in the mouth? Is it a question of hours, days or weeks to reach the measured values?
- Does the frictional force of the used surface treated wires approach the values measured in the untreated samples?
- Is it possible after a period of time, for the frictional force in the treated wires to exceed the force measured in the untreated wires, as this

would mean that the surface treated materials could be even worse than the untreated wires?
- What is the maximum time surface-treated wires are used in a clinical situation?

The Titanol Low Force and Titanol River Finish Gold archwires showed the least surface roughness. From the profilometric measurements, both of them showed a very flat and regular surface structure. The roughness (R_q) values were in the region of 0.03–0.04 μm. The similar roughness values within a single group showed a uniformity in the manufacturing process. It can be assumed that this would be true for any wire size from the same manufacturer.

The results for the Neo Sentalloy agreed with the findings from Bourauel et al. [4]. This wire also had roughness values of 5–7 times higher than the smoothest wires in our study. This was also valid for the Neo Sentalloy wires treated with ion implantation. Both the manufacturing process and the type of surface coatings played a role in the differences in roughness. The quality and grain size of the abrasives used for polishing, influences the size of the defects and the smoothness of the wire surface. Clinically, a rough surface encourages greater plaque accumulation. Both of the previously described surface treatments do not affect the original wire dimensions, or cause delamination which is the case when a coloured layer is applied to the wire. Husmann [11], Kusy et al. [16] found an increase in surface roughness after clinical use in their studies. This was also described in our study. The amount of abrasive influence from tooth brushing, i.e. the brush bristles and the abrasive in the toothpaste play, is unknown. Factors affecting surface roughness are likely to be the action of the wire sliding through the bracket and the type of fixation, i.e. elastomer or steel ligatures. The surface roughness was found to be increased not only in the area which was in contact with the bracket but also in the interbracket section of the wire. This implies that there must be some other exogenous factors which affect the surface roughness of the wire. A possible factor may be differences in diet. Further studies are needed to gain more information about these other influences on changes in frictional effects.

Similar to the findings in literature, no correlation was found between surface roughness and friction [4], however surface roughness is an integral part of the wire's properties and affects corrosion and biocompatibility. A rough surface also

leads to more plaque accumulation and therefore a greater risk from gingivitis or caries.

Conclusion

Initially, the surface treated wires demonstrated significantly ($p < 0.01$) less friction than the non-treated wires. The Titanol Low Force River Finish Gold (Forestadent, Pforzheim, Germany) wires showed least friction of all samples before oral exposure and theoretically should be more conservative on anchorage. Use of these wires in the mouth however showed that the initial effect was significantly reduced.

All wires showed an increase in friction when exposed to the oral environment. Treatment of the surface of the wire by ion implantation has therefore questionable benefits to the frictional properties of the wire when in clinical use. Further studies are needed to establish whether changing the wires more frequently would be beneficial. All of the wires investigated in this study had less surface roughness before clinical use, which is beneficial with respect to corrosion and biocompatibility. Since all wires showed an increase in surface roughness resulting from clinical use, further studies are needed to see whether in self-ligating bracket systems, where wires are used for a greater length of time, a further deterioration in surface roughness would be experienced.

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