Effect of different media on frictional forces between tribological systems made from self-ligating brackets in combination with different stainless steel wire dimensions

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The purpose was to determine the effect of different environments (artificial saliva, human saliva, distilled water, dry storage) on frictional forces between various tribological systems made from self-ligating brackets in combination with stainless-steel wires (dimensions: 0.016″×0.022″, 0.018″×0.025″ and 0.019″×0.025″). An universal testing-machine applied a normal force of 1 N. Two-way ANOVA and Tukey *post-hoc* tests (α=5%) were used. Saliva had significantly higher frictional forces ($p<0.001$). Yet, the influence of the media depends on the wire dimensions. The results were not as straightforward as in 0.018″×0.025″, which had a clear order (dry storage<water<artificial saliva<human saliva, $p<0.001$ each). Except for human saliva, wire dimensions differed significantly from each other ($p<0.001$). Increasing wire cross-sections increases frictional force. Thus, saliva acts as adhesive. High frictional forces of larger wires are attributed to the contact between latch and wire. Still, *in-vitro* experiments can only approximate the quasi-static tooth movement and the various fluids in the mouth.

Keywords: Artificial saliva, Friction, Stainless steel wire, Self-ligating bracket

INTRODUCTION

Friction between archwires and brackets is receiving much attention in clinical orthodontics, because it affects the force transmitted to the teeth and thus greatly influences the efficiency of the treatment process. The reason for the occurrence of frictional forces between the archwires and the surfaces of the brackets' slots are the applied normal forces which press the archwire against the bottom of the slot, possibly combined with other less well-defined forces resulting from binding, notching or from the used ligature of different kinds. When the applied clinical forces are adequate to overcome friction between bracket and wire, tooth movement occurs[1].

Technically, the contact between bracket and wire is called a "tribological system", which in general consists of two contacting bodies and an environment relevant to the friction between the two bodies (intermediary fluid). Hence, the sliding behavior at the interface of the bracket-wire system is controlled by the friction between the two bodies and may be affected by numerous factors, such as:

a) The geometry, slot size and design of the bracket[2-4].
b) The size, shape, alloy and physical properties (*i.e.* hardness) of wire and bracket[5-7].
c) The method of ligation, the angulation and torque between the bracket's slot and the orthodontic wire[1,8].
d) Some intraoral variables such as saliva itself[9-13].

e) The surface morphology and roughness of the bracket as well as of the wire[14].

The relationship between the resulting frictional force F_R and an associated applied normal force F_N is rather simple: $F_R=\mu \cdot F_N$ where μ is the so-called frictional coefficient. In case of orthodontic appliances, a couple of other forces may have to be added: $F_R=\mu \cdot (F_N+F_{Lig.})+F_{B/N}$, in which $F_{Lig.}$ stands for the additional normal force resulting from either a self-ligating bracket latch or from a conventional ligature pressing the archwire actively into the slot, while $F_{B/N}$ stands for additional forces resulting from binding or notching between archwire and bracket.

The occurrence of the above mentioned combined frictional forces between archwire and bracket may have caused a significant loss of clinically relevant forces and moments during orthodontic treatment, which may be as much as 12–74% of the total force applied for tooth movement[15]. Furthermore, the apparent friction has varying implications for the different phases of the orthodontic treatment[16]. For the initial phase of the orthodontic treatment, low friction is extremely important, as the goal of this stage is alignment or levelling of teeth. Therefore, higher levels of friction cause unwanted or unpredicted transmitted forces and moments and possibly damage the periodontal tissue. These side effects may lead to difficulties in moving teeth smoothly and continuously, so that for example an extraction space closure may fail[6,17,18]. As a result, methods to lower friction remain receiving attention in order to assure the desired tooth movement in orthodontic treatment[19].

Saliva, as an inevitable part of the tribological system under investigation, has been studied by different research groups so far in order to evaluate orthodontic appliances in sliding[9-11,13,20-22]. However, the function of artificial saliva in investigations of orthodontic frictional resistance has always been controversial, as it may either act as lubricant or as adhesive. Some researchers showed artificial saliva produces higher friction, while others found out that artificial saliva decreases friction[9,10,20-23].

The above mentioned findings are attributed to numerous mechanisms, such as variations in artificial saliva composition or viscosity, different normal forces applied to the contact surfaces, operation techniques or even the presence of a boundary sacrificial layer[9,11,13,20,24-27]. Artificial saliva has only water and electrolytes in common with human saliva, which shows a higher degree of compositional variability due to the presence of proteins, enzymes, mucins, cells and bacterial products which are considered specific for human saliva[28]. The difference regarding the composition of human saliva and artificial saliva may lead to the different performance in frictional force of tooth movement[26].

The aim of the present study was to investigate the influence of different testing fluids on the frictional forces between various tribological systems made from stainless steel brackets in combination with stainless steel archwires of different cross-sectional sizes.

MATERIALS AND METHODS

The present study was conducted on 36 metal active self-ligating brackets (BioQuick®, Forestadent®, Pforzheim, Germany) with a 0.022″ slot size. Prescriptions of the brackets with torque and angulation were compensated in the testing machine using multiple rotation stages, goniometric stages as well as linear stages. 36 stainless steel archwires with the dimensions of 0.016″×0.022″, 0.018″×0.025″ and 0.019″×0.025″ (Table 1) were chosen

for the experiment.

Besides the dry condition, three different fluids were added to the frictional system and the resulting frictional forces were compared to each other. The fluids were distilled water, whole human saliva, and artificial saliva. These fluids were applied to the bracket-wire combination by means of a flexible tube attached to a syringe, which dripped the fluids at a rate of 3 mL/min. The dry condition served as a control group. Human fresh saliva used for this current experiment was collected from a donator as previously published[11]. Whole human saliva was obtained immediately before the respective experiments and produced without additional stimulation. Glandosane Neutral® (Cell Pharm, Bad Villbel, Germany) was used as artificial saliva.

The measurement program was realized using Labview 2012® (National Instruments, Austin, TX, USA). All experiments were performed at (36 ± 1)°C in an air chamber with the temperature being controlled by a proportional-integral-derivative (PID) thermostat (REX-C100, RKC Instrument, Saitama, Japan). An universal testing machine (Instron® 4444, Instron®, Norwood, MA, USA) was used to pull the wire through the bracket. After fixation of the arch wire between two clamps the wire was ligated into the bracket slot which was connected perpendicular to a six-axis force torque (F/T) sensor (Nano 17 SI-25-0.25, ATI, Industrial Automation, Apex, NC, USA) with a measurement range of ±25 N and a resolution of 0.007 N on the adjustment stages (Fig. 1). The sample rate was ten force measurements per second. Before starting the measurement, the normal force F_N of 1 N was applied to the sample by means of the adjustment stages. All archwires and brackets used in this study were cleaned with 95% ethanol and air-dried prior to testing in order to remove organic residues.

During measurement, the wire traveled over a distance of 3 mm at a constant speed of 10 mm/min through the slot of the bracket using the crosshead motion of the universal testing machine. The speed of

Table 1 Mean frictional force±standard deviation (N) of all tribological samples (n=204) measured with a normal force of 1 N applied to the bracket

Media	Dimensions of orthodontic wire used for frictional test			ANOVA	
	0.016″×0.022″ (S)	0.018″×0.025″ (M)	0.019″×0.025″ (L)	p value	Subgroups
Dry (D)	0.273±0.082 N	0.889±0.086 N	0.989±0.133 N	<0.001	S:M:L
Water (W)	0.295±0.074 N	0.720±0.075 N	1.087±0.069 N	<0.001	S:M:L
Human saliva (H)	0.486±0.079 N	1.052±0.214 N	1.130±0.183 N	<0.001	S:M/L
Artificial saliva (A)	0.448±0.142 N	1.204±0.183 N	1.963±0.405 N	<0.001	S:M:L
p value	<0.001	<0.001	<0.001	—	—
Subgroups	D/W:A/H	D:W:A:H	D/W/H:A	—	—

p Values indicate the overall differences between the subgroups. The subgroups shown indicate the parameters, which do not differ significantly (stated by "/") or differ significantly (":"). The capital letters in parentheses show the abbreviations for the subgroup comparison.
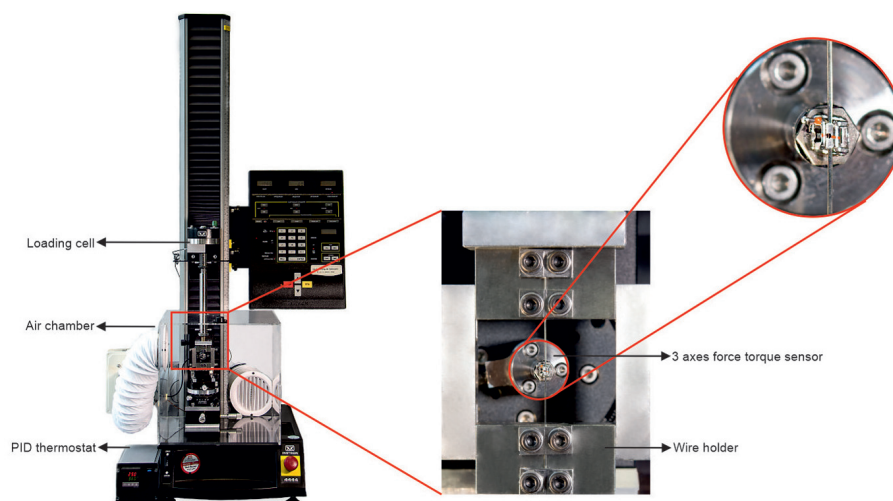
Fig. 1   Experimental setup consisting of a load cell and the bracket-wire combination
with the sensor.
All tests were performed at (36±1)°C in a chamber where the temperature was
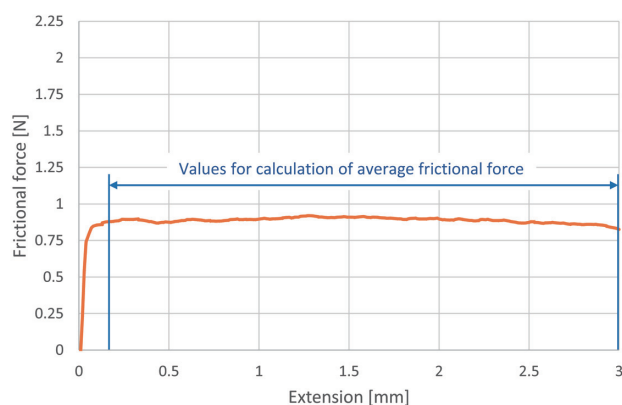controlled by a PID thermostat.

Fig. 2   Exemplary trace plot obtained from one frictional
force measurement against travel distance at 1 N
normal force.
The self-ligating bracket used was made from
stainless steel. The frictional force was calculated
by using the average values of all measurement
series for one sample kind (up to 30 sample runs)
between 0.2 and 3.0 mm.

the testing machine was chosen based on a literature
search. As reported by previous studies the velocity of
orthodontic tooth movement is as slow as 0.023 µm/min
and the tooth sliding movement is not continuous at
this extremely low velocity for all situations that occur
in clinical treatment[29,30]. Frictional force values were
measured by the force/torque sensor. The frictional force
was calculated by averaging the measured values of all
series of one sample kind from the measured force along
the travel range between 0.2 and 3 mm (Fig. 2).

All sample runs were conducted with the normal
force F_N of 1 N. The force of 1 N was used in previous

studies[21] and found in own measurements of different
ligature types. It is applied by pressing the bracket
slot against the archwire by means of the adjustment
stages and controlled by the force/torque sensor. The
corresponding coefficients therefore may be calculated
from the frictional force by $F_R=\mu \cdot F_N$. For the purpose of
minimizing the influence of the experimental error, all
samples are tested in random order with 4–5 repetitions
for each sample.

The descriptive statistics included mean values,
standard deviations (SD) for each testing group.
ANOVA, Two-way ANOVA and Tukey-HSD *post hoc*
tests were used to compare and indicate significant
differences between the impact of different environments
and archwire dimensions on the frictional values.
Calculations were carried out using SPSS 25 (IBM,
Armonk, NY, USA), with a significance level of $\alpha=5\%$.

RESULTS

The results of this study showed that the media water,
artificial saliva and human saliva influenced friction
depending on the wire dimension used. The behavior of
the media with respect to friction was different for the
individual wire dimensions.

When comparing the media with each other there
were significant differences in pairwise comparisons for
some media tested at all arch wire dimensions ($p<0.001$;
Table 1). Both saliva media had higher frictional forces
(>0.4 N) and did not differ significantly from each other
at the small dimension of 0.016″×0.022″ (Fig. 3). They
formed a homogenous subgroup that differed from the
homogenous subgroup dry test condition (0.273 N) and
water (0.295 N) ($p<0.001$; Table 1). In contrast there
was a significant difference between all media tested
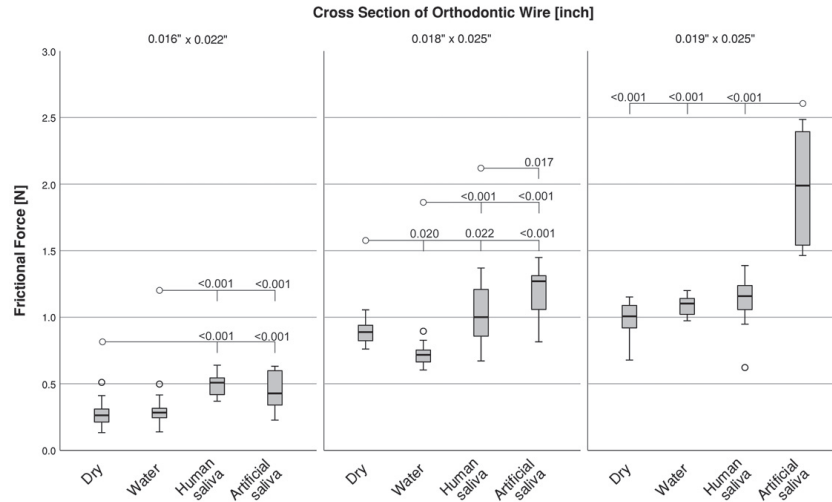($p<0.001$) for archwire dimensions of 0.018″×0.025″

Fig. 3   Comparison of the effect of different media on frictional forces measured for all dimensions tested.
Media were separated by the cross section of the orthodontic wires. Effect of the environmental states was analyzed by means of one-way ANOVA. Only significant comparisons after Tukey *post-hoc* test are indicated by "○" defining the objects of comparison.
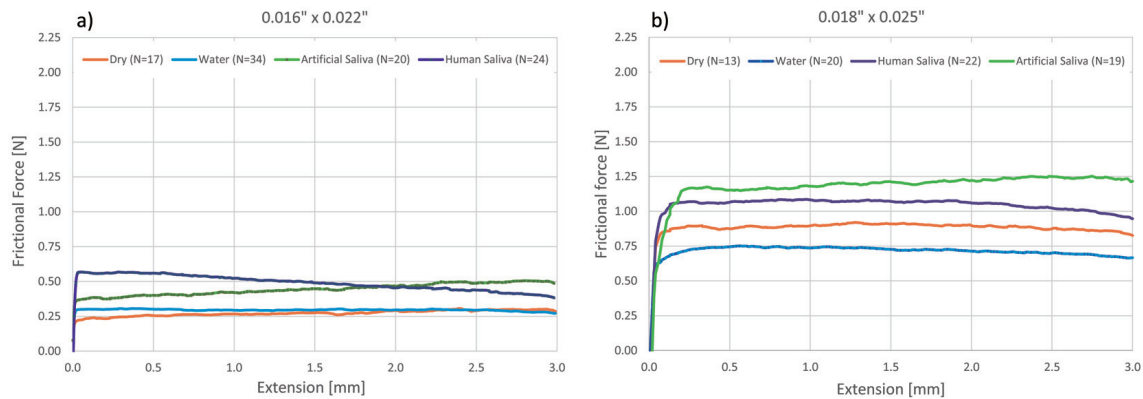

Fig. 4   Results from frictional testing for wire sizes S (A) and M (B) and all media tested. The normal force applied in all tests is 1 N.

(Fig. 4B), with the highest values for artificial saliva (1.204 N) and the lowest values for water (0.720 N) (Table 1). Artificial saliva had the highest frictional forces (1.963 N) and differed significantly from all the other media (*p*<0.001; Table 1) at the largest archwire dimension tested (0.019″×0.025″). The remaining media showed no significant differences amongst each other. Thus, the influence of the various media tested must be considered in relation to the wire dimensions used. The results were not always as straightforward as in the dimensions of 0.018″×0.025″, which had a clear order of the media (dry storage<water<artificial saliva<human saliva) and a significant difference between all media tested (*p*<0.001).

An increase in the wire dimensions led to significantly higher values of the frictional forces (Table

1). The effect of wire dimensions on the frictional force is shown in Fig. 3. Larger wire cross sections showed in general a higher level of frictional force as compared to the 0.016″×0.022″ wire (Fig. 4A). For example, a 0.016″×0.022″ wire stored in water resulted in a frictional force of 0.295 N in the tribological system compared to 0.720 N and 1.087 N at wire dimensions of 0.018″×0.025″ and 0.019″×0.025″, respectively. Similar observations were made for dry storage and artificial saliva (Table 1). Thus, when comparing the dimensions for dry storage and the media water and artificial saliva, all wire dimensions tested differed significantly from each other (*p*<0.001; Table 1). Yet, for the medium human saliva there was no significant difference between dimensions 0.018″×0.025″ and 0.019″×0.025″ (Table 1). Still, these wire dimensions resulted in higher friction (1.052 N and

1.130 N respectively) and differed significantly ($p<0.001$) from the small dimension of 0.016″×0.022″ (0.486 N).

According to two-way ANOVA tests both variables (media and wire dimension) and their combinations had large effects ($\eta^2 \geq 0.14$) and significantly influenced frictional forces measured ($p<0.001$). Wire dimension ($\eta^2 = 0.85$) had a greater effect than storage medium ($\eta^2 = 0.60$). Individually, both variables had greater effects on frictional forces than combined ($\eta^2 = 0.46$).

DISCUSSION

Both dry and moist conditions exist in the oral cavity[16]. Therefore, *in-vitro* research about friction between bracket and wire needs to take the oral environmental media into consideration[22]. The effect of both human as well as artificial saliva on friction is discussed controversially in the literature. Saliva can act either as a lubricant[9,23] or as an adhesive[9,12,22,25,31] or may even have no measureable effect at all[32]. When comparing wet and dry conditions there are also conflicting claims with frictional force either being reduced[9] or increased under dry condition[11].

In the present study, human as well as artificial saliva is observed to act as adhesive and has the effect of increasing frictional forces in all bracket-wire combinations, which is similar to findings from previous studies[12,13,25,31]. The differences in friction may result from varying constituents in artificial compared to human saliva as well as the presence of mucins in the latter[26,33].

From the technical point of view the frictional coefficient of a wet metal-metal friction system can generally be expected to be lower than for a dry metal-metal combination under the same test conditions. However, in very few cases, where the wetting agent has adhesive properties and the shearing motion is very slow or even almost static, the above mentioned lubricating effect of a wetting medium may be replaced by an adhesive effect leading to an increase of the frictional coefficient. Besides the slow speed of motion this also requires a very moderate amount of surface contact pressure. Under the given test conditions of the present study at least the last-mentioned requirement appears to be fulfilled as the normal force F_{normal} of 1 N translates to a very small amount of contact pressure P:

$$P = \frac{F_{normal}}{A_{contact}} = \frac{1\,\text{N}}{0.457\,\text{mm} \times 3.6\,\text{mm}} \approx 0.61\,\frac{\text{N}}{\text{mm}^2}$$

The contact area $A_{contact}$ in the above equation is calculated from the measured length of the bracket times the given width of the 0.018″ orthodontic wire, leading to values of 0.68 N/mm^2 for the smallest wire with 0.016″ width. While the contact pressure is irrelevant for the frictional coefficient, it may well play a role for the adhesion between two metal surfaces with an adhesive fluid being present: under high contact pressure, the lubricant may be pressed out of the lubrication gap, which can definitely be excluded, in the given

experimental setup. It is important to remember that the calculated contact pressures in both, the described experiment as well as during clinical use are at least two orders of magnitude smaller as compared to "usual" technical tribo-systems.

Similar to other research groups, the frictional force measurements in the present paper are carried out at a travel speed of 10 mm/min, which is about 10^5 times higher than the typical clinical speed of tooth motion. Even though the speed of motion does affect neither the frictional force nor the frictional coefficient directly, there is a basic difference resulting from the experimental simplification. As the clinical speed of travel may be considered quasi-static, other mechanisms than just pure friction need to be considered. Yet measuring and isolating the numerous variables affecting friction is clinically not feasible[34]:

- The adhesive forces resulting from human saliva under static load conditions may not be neglected in clinical use.
- The effect of multiple loading and unloading cycles on orthodontic wire and bracket during chewing with lateral forces at least one order of magnitude higher than the applied normal force of 1 N should be considered for the bracket-wire friction. It may be well-suited to break up any possible saliva-induced adhesion between the two components.
- Furthermore, there are all kinds of additional substances with chemical or mechanical impact inserted into the frictional system during eating, which will have a big effect on frictional forces during clinical use. The experimental setup reported in this paper as well as any other setups found in literature cannot reflect such complex frictional systems.

Therefore, *in-vitro* experiments can only reflect tooth movement to a limited extent. They give, however, an idea of the complexity of the sliding arch mechanism in orthodontic therapy. In this study larger wire cross sections show in general a higher level of frictional force as compared to the 0.016″×0.022″ wire. It can be concluded that there may be another effect than just pure friction initiated by normal force leading to this finding. It can be shown that the increase in frictional force may be attributed to the presence of an "active clip" in the applied self-ligating bracket, which has no contact if the used wire has a smaller cross section (*e.g.* 0.022″ in height), while there is contact between wire and latch if the bigger wire cross sections are used (0.025″ in height) (Fig. 5). The use of active type self-ligating brackets enables three-dimensional control of the tooth positions in later treatment phases. With passive type self-ligating brackets this is only possible to a limited extent. Therefore, active type brackets were used in this study. Here, an influence on friction was to be expected; with passive ones, no influence was naturally to be expected.

This assumption was verified by a simple qualitative experiment, which was carried out after the frictional force measurements: a wire of 0.016″×0.022″ was ligated
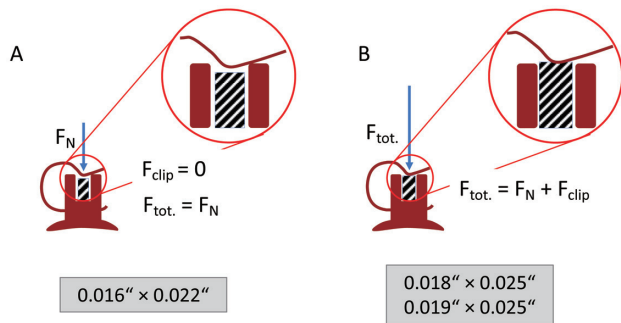
Fig. 5 Effect of the active clip (F_{clip}) on the total normal force ($F_{tot.}$) of the used self-ligating bracket: A) when smaller wire profiles are used, there is no contact between the latch and the wire. B) In case of higher wire profiles there is a substantial contact between wire surface and the latch.
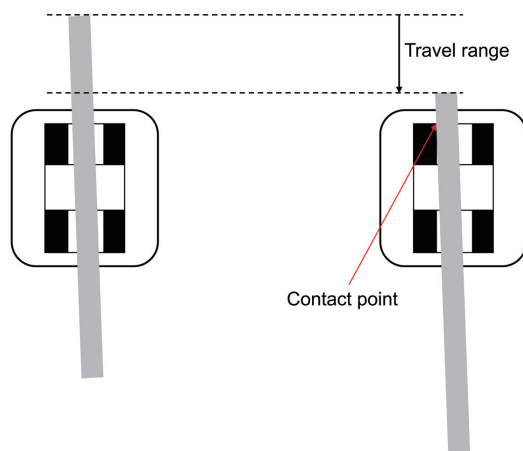

Fig. 6 Visualization of the effect of minor misalignments between archwire and bracket slot.
During the 3 mm travel range of the wire the pressure at the contact point will constantly increase. If the contact pressure reduces during the travel range, the slope of the frictional force curve will be negative.

into the bracket on a laboratory bench. Afterwards, the bracket was moved to the vertical position, which caused the wire to fall out of the slot by its own weight. However, this was not the case if a larger wire cross section (*e.g.* 0.018″×0.025″) was used. This gives evidence that there must be an additional frictional force between orthodontic wire and bracket latch.

Another aspect to be discussed is about the slope of the frictional force curves (which can be seen for instance in Fig. 4A) for the "human saliva" samples. In this case the slope is negative (−0.006 N/mm) and appears to be more or less constant over the entire length of the travel range. There are similar findings also for a few other samples tested, some of which have a positive and others a negative sign. The reason for the appearance of a slope,

no matter if negative or positive, is explained by minor invisible alignment errors between the archwire and the bracket slot, so that the archwire has slight contact with the edges of the bracket. This contact force, which adds to the normal force, may either decrease or increase if the wire is pulled through the bracket slot, generating either more or less contact pressure, which in return leads to an additional frictional force (Fig. 6).

CONCLUSIONS

1. Application of different media impact the frictional forces measured. Their influence decreases with larger wire cross sections, as wire dimension had a greater effect than storage medium.
2. *In-vitro* experiments on friction are able to describe clinical problems qualitatively. They can neither reflect the quasi-static tooth movement occurring in orthodontic treatment nor the various components of fluids present in the mouth.
3. Based on the condition of the present *in-vitro* study, it can be concluded that frictional force was higher in the wet state. Saliva acted as adhesive and increased the frictional values. The frictional values performed lowest in the dry condition.
4. Larger wire dimensions exhibit the highest frictional forces, which is attributed to the active contact between the active bracket latch and the wire surface. This may be suitable for torque control at later stages of treatment.

ACKNOWLEDGMENTS

CONFLICTS OF INTEREST

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