Resistance to sliding in orthodontics: misconception or method error? A systematic review and a proposal of a test protocol

Resistance to sliding (RS) between the bracket, wire, and ligature has been largely debated in orthodontics. Despite the extensive number of published studies, the lack of discussion of the methods used has led to little understanding of this phenomenon. The aim of this study was to discuss variables affecting RS in orthodontics and to suggest an operative protocol. The search included PubMed®, Medline®, and the Cochrane Library®. References of full-text articles were manually analyzed. English-language articles published between January 2007 and January 2017 that performed an in vitro analysis of RS between the bracket, wire, and ligature were included. Study methods were analyzed based on the study design, description of materials, and experimental setup, and a protocol to standardize the testing methods was proposed. From 404 articles identified from the database search and 242 records selected from published references, 101 were eligible for the qualitative analysis, and six for the quantitative synthesis. One or more experimental parameters were incompatible and a meta-analysis was not performed. Major factors regarding the study design, materials, and experimental setup were not clearly described by most studies. The normal force, that is the force perpendicular to the sliding of the wire and one of the most relevant variable in RS, was not considered by most studies. Different variables were introduced, often acting as confounding factors. A protocol was suggested to standardize testing procedures and enhance the understanding of in vitro findings.

Key words: Bracket, Wire, Biomaterial science

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INTRODUCTION

Friction (FR) is defined as the resistance to motion when one object moves tangentially against another (Figure 1). Thus, friction is a tangential force parallel to the sliding direction, and proportional to the coefficient of friction ($\mu$) and to the normal force (NF), which is perpendicular to the surface of contact:

$$\text{FR} = \mu \times \text{NF}$$ (1)

Friction, also known as classical friction, can be further divided into ploughing (PL), roughness interlocking (IN), and shearing (SH):

$$\text{FR} = \text{PL} + \text{IN} + \text{SH}$$ (2)

However, resistance to sliding (RS) is a more comprehensive concept than friction and comprises friction, binding (BI), and notching (NO):

$$\text{RS} = \text{FR} + \text{BI} + \text{NO}$$ (3)

Thus:

$$\text{RS} = \text{PL} + \text{IN} + \text{SH} + \text{BI} + \text{NO}$$ (4)

Rather than by the mere friction, orthodontic biomechanics is influenced by the RS since applied tangential forces, which are orthodontic forces, must overcome the RS in the opposite direction to allow tooth movement. Thus, a higher RS requires greater orthodontic forces. However, forces of greater magnitude do not imply an increased load on the anchorage teeth, despite the fact that potential anchorage loss was considered one of the disadvantages of high RS. This being said, controlling differential forces is still fundamental in orthodontics and the mechanical basis of RS still require clarifications.

Wire-slot interactions should be controlled in three dimensions, i.e., the first (I), second (II), and third orders (III), and the RS can be respectively generated on each plane, apart III since the slot has no surfaces on it:

$$\text{RS} = \text{RS}_I + \text{RS}_{II}$$ (5)

Lastly, since the components involved in RS during orthodontic movement are the bracket, the wire, and the closing system; each of these factors may have specific characteristics in terms of shapes and chemical and mechanical properties that contribute in different magnitudes to the RS.

Since friction is proportional to the normal force, and binding and notching are also affected by the normal force generated by wire deflexion when the critical contact angle ($\theta$) is exceeded, RS is mainly determined by the normal force applied to each of the above-mentioned orders (Equation 5). With regard to this, ligating methods play a primary role, and changes in the spatial configuration or elastic deformation of the mechanical components may also affect RS. Furthermore, additional variables may influence RS through the coefficient of friction, such as material compositions and lubricants.

Despite the considerable amount of published literature on RS, including reviews analyzing the effects of several related parameters, and because of the apparent disagreement between in vitro tests and clinical trials, the contribution of several variables involved in the phenomenon still require clarification.

The objectives of the present review were to identify variables involved in the in vitro evaluation of RS in orthodontics in an attempt to clarify the reasons behind the discrepancies among in vitro studies and between in vitro and clinical findings. The present
Table 1. Descriptions of the variables relevant to resistance to sliding

| Variable | Description |
|----------|-------------|
| **Study design** | |
| Number of tests* | The number of times that the same test has been repeated |
| Aligning method* | The method used to align the slot of the bracket in a neutral position relatively to the sliding direction |
| Friction type* | The type of friction evaluated during the test (e.g. static) |
| Static friction evaluation* | The criteria used to evaluate the static friction (e.g. max force) |
| Dynamic friction evaluation* | The criteria used to evaluate the dynamic friction (e.g. max force) |
| Applied normal force (N) | The force applied to the archwire to hold it into the slot (e.g. ligating force of 200 g) |
| Load cell (N) | The range of the load cell of the mechanical testing machine (e.g. 100 N) |
| Surface evaluation | The analysis of the surface of the materials (e.g. scanning electron microscopy) |
| **Materials** | |
| Bracket | |
| Type* | The type of bracket used (e.g. self-ligating) |
| Slot height (mil)* | The occlusal-gingival dimension of the slot (e.g. 22 mil) |
| Slot width (mil) | The mesio-distal dimension of the slot (e.g. 120 mil) |
| Slot depth (mil) | The bucco-lingual dimension of the slot (e.g. 28 mil) |
| Slot material* | The material in which the slot is made (e.g. stainless steel) |
| Angulation prescription (°) | The angulation of the bracket slot (“tip”) (e.g. +5°) |
| Inclination prescription (°) | The inclination of the bracket slot (“torque”) (e.g. +5°) |
| In-out prescription (mm) | The bucco-lingual distance of the slot from the base of the bracket (e.g. 0.5 mm) |
| Archwire | |
| Size (mil)* | The width of the wire measured on the two sides of its cross-section (e.g. 16 × 22 mil) |
| Material* | The material in which the wire is made (e.g. stainless steel) |
| Form | The form of the arch wire used (e.g. ovoid) |
| Ligature | |
| Size (mil) | The diameter of the cross-section of the ligature (e.g. 10 mil) (if applicable) |
| Material* | The material in which the ligature is made (e.g. stainless steel) (if applicable) |
| Relaxation time (min) (if applicable) | The time waited before testing to allow the relaxation of elastic ligatures (e.g. 5 min) |
| **Experimental setup** | |
| Number of brackets* | The number of brackets used during the test, in which the wire slides during the test (e.g. 5) |
| Bonding material | The method used to stabilise the bracket (e.g. epoxy resin) |
| Temperature (°C) | The temperature at which the test is carried (e.g. 25°C) |
| Sliding velocity (mm/min)* | The velocity of the axial displacement of the wire or of the bracket (e.g. 5 mm/min) |
| Sliding duration (min) | The duration of the test (e.g. 5 min) |
| Sliding length (mm) | The amount of displacement (e.g. 5 mm) |
| Wet/dry conditions | If the experiment is carried in dry or wet conditions (e.g. artificial saliva) |
| Torque moment (g × mm) (if applicable) | The moment applied on the bracket or arch wire during the test (e.g. 5 g × mm) (if applicable) |
| Experimental angulation (°) (if applicable) | The angulation (“tip”) added experimentally, on top of the prescription of the bracket (e.g. +5°) (if applicable) |
| Experimental inclination (°) (if applicable) | The inclination (“torque”) added experimentally, on top of the prescription of the bracket (e.g. +5°) (if applicable) |
| Experimental in-out (°) (if applicable) | The in-out (“rotation”) added experimentally, on top of the prescription of the bracket (e.g. +5°) (if applicable) |
| Vertical misalignment (mm) (if applicable) | The amount of vertical misalignment between two or more bracket (e.g. 5 mm) (if applicable) |
| Inter-bracket distance (mm)* | The distance between two or more bracket (e.g. 5 mm) (if applicable) |

Variables marked with an asterisk (*) were considered major variables and their reporting was used as inclusion criteria for eligibility in the quantitative synthesis.

1 mil = 1/1,000 inch.
work also suggests a step-by-step protocol to improve standardization of in vitro testing procedures.

MATERIALS AND METHODS

Eligibility criteria
Journal articles published between January 2007 and January 2017 in the English language and indexed either on Scopus© or PubMed© were considered. Only in vitro studies focusing on the evaluation of RS between the wire, bracket, and ligature were included.

Information sources, search strategy, and study selection
PubMed©, Medline©, and the Cochrane Library© databases were screened. The following search was performed: (“friction” [MeSH Terms] OR “friction” [Title] OR “resistance to sliding” [Title]) AND (“orthodontics” [MeSH Terms] OR “orthodontics” [Title] OR “bracket” [Title] OR “braces” [Title] OR “archwire” [Title] OR “wire” [Title]). Further records were identified from the references of full-text articles. Record identification was performed through title analysis, followed by an exclusion process based on the publication date and duplicate removal. Screening was carried by abstract analysis during the study selection and two authors (AP and JKHT) were assigned to the tasks of identification and assessment for eligibility.

Data items and collection
Data collection was performed by one author (AP), from a full-text analysis, and data were converted into the same units of measurement to enable inter-study comparisons. Variables were categorized into “study design”, i.e., contributing to the quality of the data but not directly to the outcome measurements, “materials”, i.e., related to the characteristics of the tested materials (further divided into “bracket”, “wire”, and “ligature” characteristics), and “experimental setup”, i.e., related to the experimental procedures (Table 1).

Summary measures and approach to synthesis
Variables of primary importance for RS were identified as “major variables” and were used as inclusion criteria during the eligibility assessment for the quantitative synthesis (Table 1); minor variables were considered in the discussion part. Despite its importance, ligation force was not used as an inclusion criterion and was analyzed in the discussion part. The prevalence (%) of the reporting of major variables among studies was assessed to provide a general picture of the information reported in the methods of published studies. Risk of bias, principal summary measures, and methods of combining the results from studies were not applicable because no study was included in the quantitative synthesis.

RESULTS

Study selection and characteristics
From 404 articles identified from the database search and 242 additional articles collected from references, 101 full-text articles were eligible for qualitative analysis, and six articles were eligible for quantitative synthesis (Figure 2).

Important major factors affecting the quality of the study were not described by most studies, such as the application of methods to initially align the slot and wire relative to each other (50%), and methods used to determine static (54%) or dynamic (68%) friction. None of the included studies calculated the normal force of the ligation method.

Relative to the materials description, the majority of the studies did not provide information about the material (48%), width, depth, inclination, or in/out prescription of the bracket slot. Furthermore, the wire form was described in only a few studies and ligature parameters such as the size and relaxation time of elastic ligatures were often omitted as well.

Description of the experimental setup was incomplete in most studies, such as in the case of the inter-bracket distance (38%), testing temperature, and sliding duration or length.

Synthesis of the results
Six studies were eligible for quantitative synthesis. However, one or more experimental parameters were different and data synthesis was not possible (Tables 2–4).

DISCUSSION

Summary of evidence
A considerable number of studies have been published on RS between the bracket, wire, and ligature; its consequences on clinical treatments have been investigated as well. Unfortunately, no uniform methodologies have been followed, leading to disagreement among results and limiting the clinical interpretation of experimental findings. For example, although Saunders and Kusy observed that nickel-titanium (NiTi) wires were related to higher RS than stainless steel (SS) ones, Peterson et al. revealed opposite findings. The ligation method provides additional examples, with some studies reporting that SS-tied brackets showed higher RS than elastomeric-tied ones, and others described an opposite relationship. The reason for such disagreement can be related to the adoption of different criteria in the data acquisition, the use of disparate testing methods, and especially the lack of uniform baselines for variables such as the applied normal force, together with the presence of possible confounding effects. Beside
previous reviews has discussed several of these variables comparing the results of published studies, the present work has focused on their methodologies in terms of study design, materials, and experimental setup adopted.

**Study design**

The aligning method utilized to establish an angular reference position, i.e., a completely passive interaction of the wire with respect to the bracket slot, is of particular importance when different types of brackets are tested to avoid the bracket prescription acting as a confounding variable. In this regard, an alignment jig should be used during bonding of the bracket, and preliminary tests without the application of normal forces should be performed to verify the absence of RS during translational displacement in the angular reference position. Furthermore, it should be considered that RS can be both of the static and dynamic types and respective evaluation methods based on peak forces or displacements should be used to discriminate between the two. Simple averages of the data as performed in some studies or unclear attribution of the values to either static or dynamic friction may lead to oversimplifications.

Lastly, since RS in orthodontics ranges between forces of relatively low magnitudes, e.g., between 1 N and 100 N, the sensitivity of the testing apparatus should be able to detect small force variations. Thus, the load cell of the testing machine, i.e., its operative load range, should have an upper limit similar to the expected maximum RS and should not be as high as 500 N or 10,000 N.

**Materials**

Although RS may be affected by the bracket type, the classification of brackets into standard (STD), self-ligating (SL), active self-ligating (ASL), interactive self-ligating (IASL), and passive self-ligating (PSL) categories does not identify dimensions, materials, or normal forces applied by their respective closure systems to
the wire. Although most studies described the bracket type (84%), the parameters necessary to understand its influence on RS were often not reported, such as the material (48%), slot width or depth, and the inclination or the in/out prescription. Furthermore, even if this information was declared, the data source was often the product manufacturer, and very few studies provided direct measurements of these parameters\(^9,46\) to find discrepancies between the declared data and actual measurements. Moreover, although positional details of the slot were reported by some authors, their relevance was lost if the previously described reference position was not determined. Despite the slot height being commonly reported (88%), a single parameter cannot represent the complex three-dimensional (3D) interaction between the bracket and wire.\(^21\) In fact, not only the slot height but also the slot width and depth determine the onset of the critical contact angles in the respective planes.\(^3\) Beyond this, the bracket width also influences the inter-bracket distance and wire elasticity,\(^49\) which have obvious consequences on RS.

Although the wire size (95%) and material (95%) were often described, the form of the wire was reported less frequently. Therefore, especially when super-elastic NiTi wires were tested, it was not clear whether wire curvature, e.g., the pre-formed U-shape, was taken into consideration.\(^16,22-25,28,30,31,34,39,43,47,50-54\) Moreover, the wire form has obvious consequences on RS, including changes in the normal force and critical contact angles, especially in the first order.\(^3,48\) (Figure 1).

In most studies, the ligature size was not measured, and when elastic ligatures were tested, only a few authors reported the relaxation time. Surprisingly, although major attention should be focused on the ligating method because of its influence on the normal force,\(^16,21,25,53\) this aspect received far less attention than the geometry of the wire and bracket.

### Experimental setup

The number of consecutive brackets affects wire elasticity, which is proportional to the inter-bracket distance, and is also related to RS.\(^49\) However, only 38% of the studies testing a multi-bracket system reported this variable. Despite the use of multiple brackets on a two-dimensional surface\(^55-60\) or even in a 3D configuration\(^56-66\) may allow the development of more accurate simulations of the clinical situation compared to that from a single bracket, it also creates challenges in understanding causal relationships between experimental variables and RS. Additionally, environmental factors such as temperature\(^66\) and the presence of dry or wet conditions\(^14\) can influence RS. For example, saliva may promote adhesive and

### Table 2. Summary of the study design characteristics of the studies eligible for quantitative synthesis

| Study | Number of tests | Aliging method* | Friction type* | Static/dynamic friction evaluation* | Static/dynamic load cell evaluation* | Load cell type (N) | Applied normal force (N) | Load cell type (N) | Surface evaluation | Static friction evaluation* | Dynamic friction evaluation* | Applied normal force (N) | Load cell type (N) | Surface evaluation |
|-------|----------------|-----------------|---------------|-------------------------------------|--------------------------------------|-------------------|--------------------------|-------------------|-------------------|----------------------|------------------------|--------------------------|-------------------|-------------------|
| Yeh et al. (2007)\(^7\) | 10 | SS 21.5 × 28 mil | Static/dynamic | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Cordasco et al. (2009)\(^7\) | 12 | SS 21 × 25 mil | Static | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Doshi and Bhad-Padil (2011)\(^7\) | 10 | SS 21 × 28 mil | Dynamic | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Pacheco et al. (2011)\(^7\) | 5 | U-shape SS 21 × 25 mil | Static | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| Uribe et al. (2012)\(^7\) | 9 | SS 21.5 × 28 mil | Dynamic | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| de Lima Mendonça et al. (2014)\(^7\) | 21 | SS 21.5 × 28 mil | Static | Mean of max forces | Mean of max forces | ND | ND | ND | ND | ND | ND | ND | ND | ND |

SS, Stainless steel; ND, not detected; SEM, scanning electron microscopy.

*Counted for inclusion in the quantitative synthesis.

1 mil = 1/1,000 inch.
| Study                      | Material Type | Slot height (mil) | Slot width (mil) | Slot depth (mil) | Slot material* | Angulation prescription (°) | Inclination prescription (°) | In/out prescription | Size* (mil) | Material*† | Form | Size (mil) | Material* | Relaxation time (min) |
|---------------------------|---------------|------------------|------------------|------------------|----------------|----------------------------|----------------------------|---------------------|-------------|------------|------|-----------|-----------|----------------------|
| Yeh et al. (2007)         | PSL           | 22               | ND               | ND               | SS             | ND                         | ND                         | ND                  | 14          | NiTi       | ND    | ND        | EL        | 3                     |
| Cordasco et al. (2009)†   | PSL           | 22               | ND               | 28               | SS             | +2                         | -7                         | ND                  | 21 × 25     | SS         | Straight | 10 (SS) | EL        | ND        |
| Doshi and Bhad-Patil (2011)† | STD          | 22               | 78               | ND               | AuPd           | MBT                        | MBT                        | MBT                 | 19 × 25     | SS         | NITI TMA | ND        | ND        | ND        |
| Pacheco et al. (2011)†    | STD ASL PSL   | 22               | ND               | 28               | SS             | +4                         | +12                        | ND                  | 18          | SS         | Straight | ND        | EL        | ND        |
| Uribe et al. (2012)†      | STD SL        | 22               | ND               | 28               | SS             | ND                         | ND                         | ND                  | 19 × 25     | SS         | Straight | ND        | EL        | ND        |
| de Lima Mendonça et al. (2014)† | STD          | 22               | ND               | ND               | SS             | ND                         | ND                         | ND                  | 14          | NiTi       | Straight | ND        | EL        | ND        |

1 mil = 1/1,000 inch. STD, Standard; SL, self-ligating; ASL, active SL; IASL, interactive SL; PSL, passive SL; ND, not declared; NiTi, nickel-titanium; EL, elastic ligature; SS, stainless steel; AuPd, gold-palladium; MBT, McLaughlin-Bennett-Trevisi; TMA, titanium-molybdenum alloy.

Table 3. Summary of the material characteristics of the studies eligible for quantitative synthesis.
and temperature may influence the mechanical properties of wires. Nevertheless, the testing temperature was reported by only a few studies. Furthermore, although the sliding velocity was usually mentioned (89%), previous studies showed variations in RS at different velocities and it is noteworthy that the values reported, e.g., up to 20 mm/min, were far from clinical orthodontic movements by several orders of magnitude. This being said, the bonding material was not considered even though resin composite luting cement, cyanoacrylate cement, and epoxy resin might exhibit different elasticities that influence bracket movement.

Quantitative synthesis

Six studies were eligible for quantitative synthesis. Nevertheless, parameters were different in terms of the bracket type (STD, ASL, PSL), sliding velocity (from 0.5 to 6 mm/min), inter-bracket distance (from 4.5 to 11 mm), number of brackets tested (from 1 to 5), wire material (SS, titanium-molybdenum, or NiTi), wire size (0.014″, 0.018″, 0.016″ × 0.022″, 0.017″ × 0.025″, 0.019″ × 0.025″, or 0.021″ × 0.025″), and thus a quantitative synthesis was not possible (Tables 2–4). Besides these discrepancies, it would have been difficult to attribute the differences in RS to any of the reported variables because of the scarce information on the applied normal force.

Suggested protocol

A 23-step operative protocol (Table 5) was suggested to standardize and improve the quality of future studies. Unfortunately, the standardization of some parameters, such as the tying force of the metallic ligatures, is far from being practical, making it controversial to control the applied normal forces. In fact, only a few studies attempted to quantify the ligation force in standard brackets. Regarding SL brackets, although in ASL and IASL brackets the force of the closure system can be measured through the constant of elasticity of the clip, comparisons between different types of brackets are still challenging. Lastly, in agreement with their definition, PSL brackets have no active component and thus no normal force is generated by the ligating system of the bracket. In this case, it is the wire (through its elastic deformation) that generates the normal force by contacting the walls of the slot. Although this also happens on the surface of the slot of standard brackets, the contact of a wire against a rigid closure clip is a particular characteristic of PSL brackets. Whereas in PSL brackets normal forces are determined only by the wire, they may result from the elastic deformation of both the wire and ligating system in other bracket types.

Table 4. Summary of the experimental setup characteristics of the studies eligible for quantitative synthesis

| Study                        | Number of bracket(s) | Bonding material | T (°C) | Sliding velocity (mm/min) | Sliding duration (min) | Wet/dry condition | Torque moment (g × mm) | Experiment angulation (°) | Experiment inclination (°) | Experiment in/out (mm) | Vertical misalignment (mm) | Inter-bracket distance (mm) |
|------------------------------|----------------------|------------------|--------|---------------------------|------------------------|---------------------|------------------------|--------------------------|---------------------------|--------------------------|-----------------------------|----------------------------|
| Yeh et al. (2007)            | 3                    | Cyanoacrylate    | Room   | 0.5                       | 12                     | Dry                 | ND                     | 0                        | +3                        | 0                        | +0.5                        | 0                          | 4.5                        |
| Cordasco et al. (2009)       | 3                    | Composite resin  | 37     | 5                         | ND                     | Dry                 | Dry                    | ND                       | ND                       | ND                       | ND                          | ND                         | 6                          |
| Doshi and Bhad-Patil (2011)  | 5                    | Epoxy resin      | 25     | 0.5                       | 4                      | Dry                 | Dry                    | ND                       | ND                       | ND                       | ND                          | ND                         | 6                          |
| Uribe et al. (2012)          | 2                    | Cyanoacrylate    | ND     | 20                        | ND                     | Dry                 | ND                     | ND                       | ND                       | ND                       | ND                          | ND                         | 8                          |
| de Lima Mendonça et al. (2014) | 5                  | Composite resin  | ND     | 25                        | 6                      | ND                  | Dry                    | ND                       | ND                       | ND                       | ND                          | ND                         | 6                          |
| ND                           | *Not declared.*      |                  |        |                           |                        |                     |                        |                          |                          |                          |                             |                             |
| ND, No declared.             |                      |                  |        |                           |                        |                     |                        |                          |                          |                          |                             |                             |

Lubricious behavior and temperature may influence the mechanical properties of wires. Nevertheless, the testing temperature was reported by only a few studies. Furthermore, although the sliding velocity was usually mentioned (89%), previous studies showed variations in RS at different velocities and it is noteworthy that the values reported, e.g., up to 20 mm/min, were far from clinical orthodontic movements by several orders of magnitude. This being said, the bonding material was not considered even though resin composite luting cement, cyanoacrylate cement, and epoxy resin may exhibit different elasticities that influence bracket movement.
Table 5. Step-by-step protocol

| Category           | Step     | Item                                      | Description                                                                 | Suggested standard       |
|--------------------|----------|-------------------------------------------|-----------------------------------------------------------------------------|--------------------------|
| Materials          | 1        | Bracket                                   | Define bracket type, width/height/depth of the slot, its angulation/inclination/in-out prescription, and its material. Surface evaluation is suggested. |                          |
|                    | 2        | Archwire                                  | Define wire size, material, and form. Surface evaluation is suggested.        |                          |
|                    | 3        | Ligature                                  | Define ligature size, material, and relaxation time (if elastic). Surface evaluation is suggested. |                          |
| Experimental setup | 4        | Hypothesis                                | Set the null hypothesis selecting the independent and dependent variables, with particular attention to confounding variables. |                          |
|                    | 5        | Measurements                              | Define friction type and respective methods to calculate static and dynamic friction. Measure the force utilizing load cell proportioned to the expected range of values. | Load cell 30% > experimental max force |
|                    | 6        | Randomisation                             | If different materials are tested, test them in random order.               | Sampling rate >10 Hz     |
|                    | 7        | Data recording                            | Check that the data recording setup is compatible with the experimental requirements (expected range of values, sampling rate, background noise). |                          |
|                    | 8        | Material quality                          | Use material from closed packages, and that they are not altered. Better if chosen from different production lots. Verify data declared by the manufacturer with direct measurements. |                          |
|                    | 9        | Holding system                            | Verify the stability of the device by applying forces to the components supposed to be static (e.g. the bracket). Perform mechanical testing at forces ≥ to the experimental forces. | Mobility ≤ 100 μm        |
|                    | 10       | Bracket alignment                         | The bracket slot shall be aligned in a standardized null (reference) position. Use a full size archwire for each specific slot size. | 21.5 × 28 mil archwire in 22 × 28 mil slot |
|                    | 11       | Bracket fixation                          | Bond the bracket using the aligning wire. Methods which may alter materials properties (e.g. welding) or introduce stress (e.g. bending) shall be avoided. | Light curing composite resin |
|                    | 12       | Bracket mobility                          | Test bracket mobility on the axis of the experimental force.                | No mobility at force 30% > experimental max force |
|                    | 13       | Archwire alignment                        | Test wire alignment respect to bracket slot during sliding in absence of ligatures. The absence of applied normal forces should result in the absence of frictional forces. | Clamping                 |
|                    | 14       | Archwire fixation                         | Fix the wires to the machine with clamps. Fixing methods which may alter materials properties (e.g. welding, soldering) or introduce stress (e.g. bending) shall be avoided. | No mobility at force 30% > experimental max force |
|                    | 15       | Archwire mobility                         | Test wire mobility on the axis of the experimental force.                   |                          |
|                    | 16       | Material cleaning                         | Cleaning materials and use gloves to prevent hand oil to act as a lubricant, and to remove possible residual substances from manufacturing process. | 99% ethanol              |
|                    | 17       | Number of tests/statistics                | Repeat all tests 10 times. Tests and statistical analysis shall be performed by a blinded operator. |                          |
CONCLUSION

Because of the numerous variables involved and lack of measurement of the applied normal forces, the contributions of the bracket, wire, ligature, and environmental factors to RS still require further analysis. Despite the legitimate aim to investigate complex clinical questions, the objectives of mechanical in vitro studies should be in proportion to their technical intrinsic limitations. Accordingly, the hypothesis should be specific enough to allow clear identification of the causal effects of experimental variables on RS. A protocol was suggested to achieve more objective evaluations and more relevant applications of in vitro findings to clinical treatments.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

REFERENCES

1. Besançon RM. The encyclopedia of physics. 3rd ed. New York, NY: Van Nostrand Reinhold Company; 1985.
2. Jastrzebsky ZD. The nature and properties of engineering materials. 2nd ed. New York, NY: Wiley & Sons; 1976.
3. Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. Eur J Orthod 1999;21:199-208.
4. Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod 1997;3:166-77.
5. Burrow SJ. Friction and resistance to sliding in orthodontics: a critical review. Am J Orthod Dentofacial Orthop 2009;135:442-7.
6. Kapur R, Sinha PK, Nanda RS. Comparison of frictional resistance in titanium and stainless steel brackets. Am J Orthod Dentofacial Orthop 1999;116:271-4.
7. Southard TE, Marshall SD, Grosland NM. Friction does not increase anchorage loading. Am J Orthod Dentofacial Orthop 2007;131:412-4.
8. Braun S, Bluestein M, Moore BK, Benson G. Friction in perspective. Am J Orthod Dentofacial Orthop 1999;115:619-27.
9. Yeh CL, Kusnoto B, Viana G, Evans CA, Drummond JL. In vitro evaluation of frictional resistance between brackets with passive-ligation designs. Am J Orthod Dentofacial Orthop 2007;131:704.e11-22.
10. Muguruma T, Iijima M, Brantley WA, Abulwalia KS, Kohda N, Mizoguchi I. Effects of third-order torque on frictional force of self-ligating brackets. Angle Orthod 2014;84:1054-61.
11. Kusy RP. Influence of force systems on archwire-bracket combinations. Am J Orthod Dentofacial Orthop 2009;135:442-7.
11. Savoldi F, Bonetti S, Dalessandri D, Mandelli G, Paganelli C. Incisal apical root resorption evaluation after low-friction orthodontic treatment using two-dimensional radiographic imaging and trigonometric correction. J Clin Diagn Res 2015;9:ZC70-4.

12. Saunders CR, Kusy RP. Surface topography and frictional characteristics of ceramic brackets. Am J Orthod Dentofacial Orthop 1994;106:76-87.

13. Peterson L, Spencer R, Andreasen G. Comparison of friction resistance for Nitinol and stainless steel wires and “reduced-friction” self-ligating esthetic and conventional brackets. Int J Odontostomatol 2014;8:261-6.

14. Fleming PS, DiBiase AT, Lee RT. Randomized clinical trial of orthodontic treatment efficiency with self-ligating and conventional fixed orthodontic appliances. Am J Orthod Dentofacial Orthop 2010;137:738-42.

15. Savoldi F, Bonetti S, Dalessandri D, Mandelli G, Paganelli C. Incisal apical root resorption evaluation after low-friction orthodontic treatment using two-dimensional radiographic imaging and trigonometric correction. J Clin Diagn Res 2015;9:ZC70-4.

16. Saunders CR, Kusy RP. Surface topography and frictional characteristics of ceramic brackets. Am J Orthod Dentofacial Orthop 1994;106:76-87.

17. Peterson L, Spencer R, Andreasen G. A comparison of friction resistance for Nitinol and stainless steel wire in edgewise brackets. Quintessence Int Dent Dig 1982;13:563-71.

18. Husain N, Kumar A. Frictional resistance between orthodontic brackets and archwires: an in vitro study. J Contemp Dent Pract 2011;12:91-9.

19. Kim TK, Kim KD, Baek SH. Comparison of frictional forces during the initial leveling stage in various combinations of self-ligating brackets and archwires with a custom-designed typodont system. Am J Orthod Dentofacial Orthop 2008;133:187.e15-24.

20. Oz AA, Arici N, Arici S. The clinical and laboratory effects of bracket type during canine distalization with sliding mechanics. Angle Orthod 2012;82:326-32.

21. Huang TH, Luk HS, HsuYC, Kao CT. An in vitro comparison of the frictional forces between archwires and self-ligating brackets of passive and active types. Eur J Orthod 2012;34:625-32.

22. Lombardo L, Wierusz W, Toscano D, Lapenta R, Kaplan A, Siciliani G. Frictional resistance exerted by different lingual and labial brackets: an in vitro study. Prog Orthod 2013;14:37.

23. Williams CL, Khalf K. Frictional resistance of three types of ceramic brackets. J Oral Maxillofac Res 2014;4:e3.

24. Fourie Z, Ozcan M, Sandham A. Effect of dental arch convexity and type of archwire on frictional forces. Am J Orthod Dentofacial Orthop 2009;136:14.e1-7; discussion 14-5.
37. Edwards IR, Spary DJ, Rock WP. The effect upon friction of the degradation of orthodontic elastomeric modules. Eur J Orthod 2012;34:618-24.
38. Martins MM, Teixeira AOB, Artese F, Mendes AM. Friction generated by elastomeric ligature with and without polymer coating. Braz Dent Sci 2011;14:9-12.
39. Queiroz GV, Ballester DY, Batista De Paiva J, Neto JR, Galon GM. Comparative study of frictional forces generated by NiTi archwire deformation in different orthodontic brackets in vitro evaluation. Dental Press J Orthod 2012;17:45-50.
40. Abbassy MA, Bakry AS. The effect of fluoride on beta titanium orthodontics wires' surface texture and friction resistance. Int J Dent Oral Sci 2015;2:47-52.
41. Uribe MN, Chaparro JPB, Cáceres EJG, Mazo ILP, Quijada ACR. Comparison of resistance to sliding produced by self-ligating brackets and conventional ligatures with ligated conventional elastomeric ligature and low-friction ligatures. Rev Fac Odontol Univ Antioq 2012;23:192-206.
42. Pillai AR, Gangadharan A, Kumar S, Shah A. Comparison of the frictional resistance between archwire and different bracket system: an in vitro study. J Pharm Bioallied Sci 2014;6(Suppl 1):S150-5.
43. Kumar S, Singh S, Hamza PRR, Ahmed S, Prasantham, Bhatnagar A, et al. Evaluation of friction in orthodontics using various brackets and archwire combinations-an in vitro study. J Clin Diagn Res 2014;8:ZC33-6.
44. Fathimani M, Melena GW, Romanyk DL, Toogood RW, Heo G, Carey JP, et al. Development of a standardized testing system for orthodontic sliding mechanics. Prog Orthod 2015;16:14.
45. Voudouris JC, Schismenos C, Lackovic K, Kufinec MM. Self-ligation esthetic brackets with low frictional resistance. Angle Orthod 2010;80:188-94.
46. Nucera R, Lo Giudice A, Matarese G, Artemisia A, Bramanti E, Crupi P, et al. Analysis of the characteristics of slot design affecting resistance to sliding during active archwire configurations. Prog Orthod 2013;14:35.
47. Fannonato G, Majer R, Caria MP, Esposito L, Albertzoni D, Cacciator G. The effect of Teflon coating on the resistance to sliding of orthodontic archwires. Eur J Orthod 2012;34:410-7.
48. Alió-Sanz JJ, Claro-Stucchi M, Albaladejo A, Iglesias-Conde C, Alvarado-Lorenzo A. In vitro comparative study on the friction of stainless steel wires with and without Orthospeed® (JAL 90458) on an inclined plane. J Clin Exp Dent 2016;8:e141-5.
49. Whitley JQ, Kusy RP. Influence of interbracket distances on the resistance to sliding of orthodontic appliances. Am J Orthod Dentofacial Orthop 2007;132:360-72.
50. Tecco S, Di Iorio D, Cordasco G, Verrocchi I, Festa F. An in vitro investigation of the influence of self-ligating brackets, low friction ligatures, and archwire on frictional resistance. Eur J Orthod 2007;29:390-7.
51. Pliska BT, Beyer JP, Larson BE. A comparison of resistance to sliding of self-ligating brackets under an increasing applied moment. Angle Orthod 2011;81:794-9.
52. Tecco S, Di Iorio D, Nucera R, Di Bisceglie B, Cordasco G, Festa F. Evaluation of the friction of self-ligating and conventional bracket systems. Eur J Dent 2011;5:310-7.
53. Crincoli V, Perillo L, Di Bisceglie MB, Balsamo A, Serpico V, Chiatante F, et al. Friction forces during sliding of various brackets for malaligned teeth: an in vitro study. ScientificWorldJournal 2013;2013:871423.
54. de Lima Mendonça S, Praxedes Neto OJ, de Oliveira PT, dos Santos PB, de Sá Leitão Pinheiro FH. Comparison of friction produced by two types of orthodontic bracket protectors. Dental Press J Orthod 2014;19:86-91.
55. Chang CJ, Lee TM, Liu JK. Effect of bracket bevel design and oral environmental factors on frictional resistance. Angle Orthod 2013;83:956-65.
56. Galvão MB, Camporesi M, Tortamano A, Dominguez GC, Defraia E. Frictional resistance in monocristaline ceramic brackets with conventional and nonconventional elastomeric ligatures. Prog Orthod 2013;14:9.
57. Inami T, Tanimoto Y, Yamaguchi M, Shibata Y, Nishiyama N, Kasi K. Surface topography, hardness, and frictional properties of GFRP for esthetic orthodontic wires. J Biomed Mater Res B Appl Biomater 2016;104:88-95.
58. loi H, Yanase Y, Uehara M, Hara A, Nakata S, Nakasima A, et al. Frictional resistance in plastic preadjusted brackets ligated with low-friction and conventional elastomeric ligatures. J Orthod 2009;36:17-22; discussion 13.
59. Matarese G, Nucera R, Militi A, Mazza M, Portelli M, Festa F, et al. Evaluation of frictional forces during dental alignment: an experimental model with 3 nonleveled brackets. Am J Orthod Dentofacial Orthop 2008;133:708-15.
60. Cordasco G, Lo Giudice A, Militi A, Nucera R, Triolo G, Matarese G. In vitro evaluation of resistance to sliding in self-ligating and conventional bracket systems during dental alignment. Korean J Orthod 2012;42:218-24.
61. Chung M, Nikolai RJ, Kim KB, Oliver DR. Third-
order torque and self-ligating orthodontic bracket-type effects on sliding friction. Angle Orthod 2009;79:551-7.

62. Heo W, Baek SH. Friction properties according to vertical and horizontal tooth displacement and bracket type during initial leveling and alignment. Angle Orthod 2011;81:653-61.

63. Meier MJ, Bourauel C, Roehlike J, Reimann S, Keilig L, Braumann B. Friction behavior and other material properties of nickel-titanium and titanium-molybdenum archwires following electrochemical surface refinement. J Orofac Orthop 2014;75:308-18.

64. Murayama M, Namura Y, Tamura T, Iwai H, Shimizu N. Relationship between friction force and orthodontic force at the leveling stage using a coated wire. J Appl Oral Sci 2013;21:554-9.

65. Seo YJ, Lim BS, Park YG, Yang IH, Ahn SJ, Kim TW, et al. Effect of tooth displacement and vibration on frictional force and stick-slip phenomenon in conventional brackets: a preliminary in vitro mechanical analysis. Eur J Orthod 2015;37:158-63.

66. Obaisi NA, Galang-Boquiren MT, Evans CA, Tsay TG, Viana G, Berzins D, et al. Comparison of the transformation temperatures of heat-activated nickel-titanium orthodontic archwires by two different techniques. Dent Mater 2016;32:879-88.

67. Savoldi F, Visconti L, Dalesandri D, Bonetti S, Tsoi JKH, Matlinmäki JP, et al. In vitro evaluation of the influence of velocity on sliding resistance of stainless steel arch wires in a self-ligating orthodontic bracket. Orthod Craniofac Res 2017;20:119-25.

68. Natt AS, Sekhon AK, Munjal S, Duggal R, Holla A, Gupta P, et al. A comparative evaluation of static frictional resistance using various methods of ligation at different time intervals: an in vitro study. Int J Dent 2015;2015:407361.

69. Venâncio FR, Vedovello SAS, Tubel CAM, Degan VV, Lucato AS, Lealdim LN. Effect of elastomeric ligatures on frictional forces between the archwire and orthodontic bracket. Braz J Oral Sci 2013;12:41-5.

70. Pacheco MR, Oliveira DD, Neto PS, Jansen WC. Evaluation of friction in self-ligating brackets subjected to sliding mechanics: an in vitro study. Dental Press J Orthod 2011;16:107-15.

71. Cordasco G, Farronato G, Festa F, Nucera R, Parazzoli E, Grossi GB. In vitro evaluation of the frictional forces between brackets and archwire with three passive self-ligating brackets. Eur J Orthod 2009;31:643-6.

72. Doshi UH, Bhad-Patil WA. Static frictional force and surface roughness of various bracket and wire combinations. Am J Orthod Dentofacial Orthop 2011;139:74-9.

73. Sirisaowaluk N, Kravchuk O, Ho CT. The influence of ligation on frictional resistance to sliding during repeated displacement. Aust Orthod J 2006;22:141-6.

74. Keith O, Jones SP, Davies EH. The influence of bracket material, ligation force and wear on frictional resistance of orthodontic brackets. Br J Orthod 1993;20:109-15.