Original article

Effect of tooth displacement and vibration on frictional force and stick-slip phenomenon in conventional brackets: a preliminary in vitro mechanical analysis


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Summary

Objective: To evaluate the effects of tooth displacement and vibration on frictional force and stick-slip phenomenon (SSP) when conventional brackets were used with a levelling/alignment wire.

Materials and Methods: The samples consisted of six groups (n = 10 per group) with combinations of tooth displacement (2 mm lingual displacement [LD], 2 mm gingival displacement [GD], and no displacement [control]) and vibration conditions (absence and presence at 30 Hz and 0.25 N). A stereolithographically made typodont system was used with conventional brackets and elastomeric ligatures. After application of artificial saliva, static/kinetic frictional forces (SFF/KFF) and frequency/amplitude of SSP were measured while drawing a 0.018-inch copper nickel-titanium (Cu-NiTi) archwire at a speed of 0.5 mm/min for 5 minutes at 36.5 degree celsius. Two-way analysis of variance and independent t-test were performed.

Results: Tooth displacement increased SFF and KFF (control < LD < GD, all P < 0.001) and reduced SSP frequency (control > [LD, GD], P < 0.01). Vibration reduced SFF, KFF, and SSP amplitude in the control group (P < 0.05, P < 0.05, and P < 0.001, respectively), but not in the LD and GD groups. SSP frequency was increased by vibration in the control, LD, and GD groups (all P < 0.001), and it was lower in the LD and GD groups than in the control group (P < 0.01).

Conclusions: When conventional brackets and a 0.018-inch Cu-NiTi archwire were used in the tooth displacement conditions (LD and GD), vibration did not significantly reduce SFF, KFF, or SSP amplitude.

Introduction

The resistance-to-sliding of a bracket along an archwire arises from two sources, the force of ligation and the force of binding in the absence of extreme forces that cause physical notching of the archwire (1, 2). Frictional force or resistance-to-sliding has been thoroughly investigated (3–11), and the effect of binding on frictional properties has also received attention (1, 12–16).

The effect of binding on resistance-to-sliding is important at the levelling/alignment stage because misaligned teeth result in wire deflection in contact with the edges of the bracket slots owing to crowding, rotation, angulation, and vertical discrepancy (17, 18). Because the binding may be more significant than the frictional component of resistance-to-sliding in an active configuration (12, 13), releasing the binding between the bracket slot and wire is important in orthodontic tooth movement.
Vibration can force an archwire to be released from the binding (19, 20). Thus far, two aspects of vibration in orthodontics have been studied: biological and mechanical effects. It has been suggested that vibration stimulates the periodontal tissue, resulting in accelerated tooth movement (21–24). However, vibration has also been reported to reduce resistance-to-sliding and to affect stick-slip phenomenon (SSP) (20, 25–28).

To investigate the mechanical effects of vibration on frictional force and SSP, standardization of vibration condition including frequency and force is important. Therefore, we decided to use a commercially available vibration device (AcceleDent®, OrthoAccel Technologies Inc., Bellaire, Texas, USA) for setting up the standardized vibration condition because it has fixed values of frequency of 30 Hz and force of 0.25 N.

The purpose of this in vitro mechanical study was to evaluate the effects of tooth displacement and vibration on frictional force and SSP when conventional brackets were used with a levelling/alignment wire. The null hypothesis was that there were no significant differences in the effects of tooth displacement and vibration on frictional force and SSP when conventional brackets were used with a levelling/alignment wire.

**Materials and methods**

One type of conventional metal bracket (Victory, 3M-Unitek, Monrovia, California, USA) and elastic ligature (Unistick Ligatures, American Orthodontics, Sheboygan, Wisconsin, USA) were used. The bracket was made of stainless steel (SS) and had a 0.022-inch slot. A 3-minute waiting period was applied to guarantee stress relaxation of the elastic ligatures and reproducibility of ligature force (6–8, 11). From the clinically used levelling/alignment archwires, a 0.018-inch copper nickel-titanium (Cu-NiTi) archwire (Ormco, Orange, California, USA) was selected as the test wire because it is one of the largest dimension levelling/alignment wires among the clinically available round NiTi wires, which is more easy to show the binding phenomenon than other round NiTi wires (e.g. 0.014 or 0.016 NiTi wire).

A previously used, a custom-designed typodont system (11) was re-fabricated. This typodont system had the full maxillary dentition fixed to an arch-shaped metal frame, which allowed each tooth to move individually. All teeth were ideally aligned along the ovoid arch form (OrthoForm III-Ovoid, Reference No. 701–723, 3M-Unitek) in the zero position. For accurate and reproducible bracket positioning, indirect bonding jigs were fabricated for all brackets. Each tooth had its periodontal ligament (PDL) space filled with a silicone impression material (Imprint™ II Garant™ Light Body Vinyl Polysiloxane Impression Material, 3M ESPE; Seefeld, Germany), which emulates the mobility of human teeth and functions as a stress-absorbing mechanism that can affect resistance-to-sliding (11, 29).

The samples consisted of six groups representing all combinations of (1) three types of tooth displacement (2 mm lingual displacement [LD] of the maxillary right lateral incisor, 2 mm gingival displacement [GD] of the maxillary right canine, and no displacement [control]) and (2) two states of vibration (presence and absence). Vibration was applied with an electronic device with one mode of vibration (AcceleDent®, OrthoAccel Technologies Inc., Bellaire, Texas, USA) set at a frequency of 30 Hz and a force of 0.25 N. The device was placed between maxillary and mandibular typodonts that represented a patient biting the device. The typodonts and the AcceleDent® system were held together with silicone bites and two metal fixation frames on each side in order to consistently reproduce passive bite conditions for each test (Supplementary figures of experimental conditions are provided).

Artificial saliva (Taliva®, Hanlim Pharm. Co., Ltd, Seoul, Korea) was applied to the bracket slots. The typodont system was washed out to remove artificial saliva with distilled water and alcohol immediately after each test. Then, it was dried by air syringe. Tests were conducted in a chamber maintained at 36.5 ± 0.3 degree celsius.

Static/kinetic frictional forces (SFF/KFF) and the frequency and amplitude of SSP were measured while drawing a 0.018-inch Cu-NiTi archwire at a speed of 0.5 mm/min for 5 minutes with a mechanical testing machine (Model 4466, Instron, Canton, Massachusetts, USA). The definitions of SFF, KFF, and the frequency and amplitude of SSP are listed in Figure 1. One end of the archwire extruded from the maxillary right second molar tube was gripped by a custom-designed adaptor. Each group was tested 10 times and a new wire was used each time.

A power analysis was performed to determine the sample size using a sample size determination program (Version 2.0.1, Seoul National University Dental Hospital, Registration No. 2007-01-122-004453, Seoul, Korea). The means and standard deviations derived from a previous study (11) were used for the power analysis.

A two-way analysis of variance (ANOVA) and post hoc Bonferroni test were performed to evaluate the interaction of tooth displacement and vibration with regard to SFF, KFF, and the frequency and amplitude of SSP. The independent t-test was used to

![Graph](image160x285 to 494x267)

**Figure 1.** Definitions of the variables. Static frictional force (SFF) was measured at the maximal point of the initial rise. Kinetic frictional force (KFF) was calculated by averaging frictional forces from 0.2 mm beyond or 24 seconds after the SFF point up to the end of the test. Frequency of stick-slip phenomenon (SSP) was defined as the number of peaks divided by the time of the KFF phase in minutes. SSP amplitude was measured by averaging the differences between the peak and trough of each cycle of SSP within the KFF phase.
further compare the effect of vibration on the variables according to tooth displacement type. The level of significance for all tests was set at \( P < 0.05 \).

Results

In the two-way ANOVA, there was no significant interaction between tooth displacement types and vibration conditions with regard to SFF and KFF (Table 1). However, there was significant interaction with regard to the frequency and amplitude of SSP \( (P < 0.01 \) and \( P < 0.001 \), respectively, Table 1).

Effect of tooth displacement and vibration on SFF and KFF

Both SFF and KFF were significantly increased by tooth displacement (control < LD < GD, all \( P < 0.001 \), Table 1). However, SFF and KFF were significantly reduced by vibration in the control group (all \( P < 0.05 \), Figure 2A and B), but not in the LD and GD groups.

Effect of tooth displacement and vibration on SSP frequency

The effect of vibration on SSP frequency generally decreased according to tooth displacement (control < LD < GD, all \( P < 0.01 \), Table 1); among tooth displacement types, SSP frequency in the LD and GD groups was reduced compared with that in the control group \( (P < 0.01 \), Table 1), especially under vibration conditions, while there was no significant difference among the control, LD, and GD groups under non-vibration conditions (Figure 2C). However, SSP frequency under vibration conditions was significantly increased compared with that under non-vibration conditions overall \( (P < 0.001 \), Table 1), and in the control, LD, and GD groups \( (P < 0.001 \), Figure 2C).

Effect of tooth displacement and vibration on SSP amplitude

The effect of vibration on SSP amplitude generally decreased according to tooth displacement \( (P < 0.001 \), Table 1). Under vibration conditions, SSP amplitude was increased in the LD and GD groups compared with that in the control group \( (P < 0.001 \), Figure 2D), whereas under non-vibration conditions, it was decreased in the LD and GD groups compared with that in the control group (Figure 2D). However, SSP amplitude was significantly reduced by vibration only in the control group \( (P < 0.001 \), Figure 2D), but not in the LD and GD groups.

Discussion

We attempted to develop an experimental design that simulated clinical conditions, including full dentition aligned in an arch-shaped form, use of artificial alternatives to the PDL's stress-absorbing mechanism, achievement of occlusion state between the maxillary and mandibular dentitions, application of artificial saliva, and vibration generated by the appliance used in clinics.

The finding that both SFF and KFF were significantly increased by tooth displacement (control < LD < GD, all \( P < 0.001 \), Table 1, Figure 2A and B) implies that tooth displacement produces an active configuration between bracket slot and archwire, which increases the binding. These results are in accordance with previous studies \( (1, 12, 13, 15, 16, 30, 31) \).

Vibration induced significant reductions in SFF and KFF in the control group \( (P < 0.05) \), but not in the LD and GD groups (Figure 2A and B). While this result is in accordance with previous studies reporting a decrease in frictional force in a passive configuration \( (26, 27) \), it is not in accordance with previous studies reporting a decrease in frictional force in an active configuration \( (20, 26) \). These differences may derive from differences in test design, including the use of different wires as well as dissimilarities in the alignment of brackets and in vibrating conditions.

Vibration frequency was significantly increased by vibration in the control, LD, and GD groups \( (P < 0.001 \), Figure 2C), while the amount of increase in SSP frequency was less in the LD and GD groups than in the control group \( (P < 0.01 \), Table 1). SSP amplitude was significantly reduced by vibration only in the control group \( (P < 0.001 \), Figure 2D), but not in the LD and GD groups. Thus, these findings suggest that the effect of vibration on SSP might be reduced in cases with tooth displacement due to an increase in binding compared with control (Figure 2).

An increase in SSP frequency represents an increase in the number of SSP and a decrease in the duration of binding in each SSP cycle.

| Table 1. Comparison of the variables according to tooth displacement types and vibration conditions \( (n = 10 \) per group). |
|---|---|---|---|---|---|---|
| Variables | Displacement | Non-vibration | Vibration | Significance (\( P \) value) | Displacement × Vibration |
| | Mean | SD | Mean | SD | | |
| SFF \((cN)\) | Control | 2544.90 | 149.31 | 2400.30 | 156.76 | <0.001*** | 0.055 | 0.560 |
| | LD | 2969.00 | 196.97 | 2909.20 | 160.94 | Control < LD < GD |
| | GD | 3115.20 | 114.18 | 3074.50 | 178.73 | |
| KFF \((cN)\) | Control | 2475.74 | 185.38 | 2320.81 | 137.28 | <0.001*** | 0.070 | 0.442 |
| | LD | 2913.45 | 187.61 | 2868.89 | 169.71 | Control < LD < GD |
| | GD | 3074.18 | 113.05 | 3039.28 | 176.49 | |
| SSP frequency \((cpm)\) | Control | 4.65 | 1.01 | 19.37 | 3.06 | 0.002** | <0.001*** | 0.009** |
| | LD | 4.40 | 1.15 | 15.73 | 3.09 | Control > (LD, GD) |
| | GD | 4.23 | 1.16 | 15.37 | 1.20 | Non-vibration < Vibration |
| SSP amplitude \((cN)\) | Control | 32.00 | 9.87 | 8.30 | 1.50 | 0.199 | <0.001*** | <0.001*** |
| | LD | 18.80 | 7.04 | 15.40 | 4.90 | Non-vibration > Vibration |

Two-way analysis of variance and post hoc Bonferroni test were performed. LD represents 2 mm lingual displacement of the maxillary right lateral incisor; GD, 2 mm gingival displacement of the maxillary right canine; SSP, stick-slip phenomenon; SD, standard deviation; cpm, cycles per minute.

** \( P < 0.01 \), *** \( P < 0.001 \).
A decrease in SSP amplitude corresponds to a decrease in the maximum frictional force at the binding release point. In other words, vibration can increase SSP frequency and decrease SSP amplitude although this was observed only in the control group which generated relatively low binding. Although several studies have reported the effect of vibration on resistance-to-sliding (20, 25–28), as yet there are few reported studies focusing on frequency and amplitude of SSP in detail. Thus, it was not possible to compare this study directly with other studies.

In the LD and GD groups that simulated active configurations, there were no effects of vibration on SFF, KFF, or SSP amplitude (Table 1, Figure 2A, B, and D). However, in the control group that represented well-aligned dentition, there were significant reductions in SFF, KFF, and SSP amplitude (Table 1, Figure 2A, B, and D). SSP frequency was significantly increased by vibration in the control, LD, and GD groups (Table 1, Figure 2C). Therefore, SSP amplitude might affect frictional forces more than SSP frequency. These findings suggest the possibility that changes in SSP amplitude caused by vibration can affect frictional force under certain conditions.

However, SSP amplitude exhibited opposite patterns in vibration and non-vibration groups; an increase under vibration conditions and a decrease under non-vibration conditions (Figure 2D). A decrease in SSP amplitude under non-vibration conditions is assumed to occur as follows: despite high SFF and KFF values (Table 1, Figure 2A and B), the archwire could be drawn without complete release of binding by the testing machine due to the flexibility of a 0.018-inch Cu-NiTi wire. Therefore, it is possible that the observed decrease in SSP amplitude under non-vibration conditions is due to the incomplete release of strong binding in tooth displacement groups. However, it is necessary to perform similar tests with round or rectangular SS wires to verify this assumption.

Bracket slot configuration and ligation methods have been reported to affect frictional force and critical contact angle (4, 11, 13, 17, 18, 30–34). When an archwire is engaged in the bracket slot, the effective slot dimension is mainly determined by the fourth slot wall (or ligation method) and the type of tooth displacement. Since the fourth slot wall in conventional brackets is an elastomeric ligature, the effective slot width can be increased by a ligature surrounding the bracket wings. The effective slot depth and height can also be changed via interaction between ligatures and archwires (Figure 3).

In terms of mechanical force between ligatures and archwires, there are two considering factors. First, all types of ligatures, both elastomeric and SS, apply a seating force that pushes the archwire into the bracket slot, resulting in influencing the frictional properties. Second, since the elastomeric ligature itself generates a high frictional force, it is difficult to release the binding between wire and conventional brackets. These factors can explain high SFF and KFF values and no effects of vibration on SFF, KFF, or SSP amplitude in tooth displacement groups (Table 1, Figure 2A, B, and D).

One of the limitations of this study is that it was an in vitro study. It is necessary to develop the experimental set-up further in order to...
better reflect the intraoral environment in future studies. For example, although the material used to emulate the PDL’s stress-absorbing mechanism and tooth mobility has been used in previous study (11), there is a limitation in that the in vivo PDL is not homogenous in its stress/strain characteristics (29). Moreover, it is necessary to evaluate the effects of vibration in various types of brackets, wires, and ligation methods including passive and active self-ligating brackets. Since pulling an archwire in one direction is not exactly same with the clinical situation, it is needed to alter the experiment method for more realistic simulation of the clinical situation.

The vibration device used in this study, AcceleDent®, is suggested to have an accelerating effect on orthodontic tooth movement via biological stimulation with application of 20 minutes per day in occlusion state according to company’s contention. However, there is still lack of evidence-based data about the validity and effectiveness of the device.

This in vitro study showed that vibration could positively affect decreases in SFF, KFF, and SSP amplitude and increases in SSP frequency in cases with well-aligned dentition only. There was no proof that the vibration device had a positive mechanical effect on frictional force and SSP under condition of levelling and alignment for mal-aligned dentition at this experimental set-up.

Therefore, further in vitro and in vivo studies are needed to evaluate the effects of vibration on frictional force and SSP when a rigid working wire is used for space closure. The investigation of optimal vibration conditions and application methods for efficiently reducing binding and frictional force is also required. In addition, since the seating force exerted by the ligature material might be a little bit different according to the type and amount of tooth displacement, it is needed to perform further studies about this issue. The authors hope that this study could be regarded as a preliminary study for designing more sophisticated tests and conducting further studies.

Conclusions

When conventional brackets and a 0.018-inch Cu-NiTi archwire were used, the vibrational device did not significantly reduce SFF, KFF, or SSP amplitude in the tooth displacement conditions (LD and GD) compared with well-aligned condition (control).

Supplementary material

Supplementary material is available at European Journal of Orthodontics online.
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References