

Effect of passive self-ligating bracket placement on the posterior teeth on reduction of frictional force in sliding mechanics

Kyu-Ry Kim^a
Seung-Hak Baek^{a,b}

^aDepartment of Orthodontics, School of Dentistry, Seoul National University, Seoul, Korea

^bDental Research Institute, Seoul National University, Seoul, Korea

Objective: The purpose of this study was to investigate the static (SFF) and kinetic frictional forces (KFF) in sliding mechanics of hybrid bracket systems that involve placing a conventional bracket (CB) or active self-ligating bracket (ASLB) on the maxillary anterior teeth (MXAT) and a passive SLB (PSLB) on the maxillary posterior teeth (MXPT). **Methods:** The samples consisted of two thoroughbred types (group 1, anterior-CB + posterior-CB; group 2, anterior-ASLB + posterior-ASLB) and four hybrid types (group 3, anterior-CB + posterior-PSLB-type 1; group 4, anterior-CB + posterior-PSLB-type 2; group 5, anterior-ASLB + posterior-PSLB-type 1; group 6, anterior-ASLB + posterior-PSLB-type 2) (n = 13 per group). After maxillary dentition alignment and maxillary first premolars removal in the stereolithographically-made typodont system, a 0.019 × 0.025-inch stainless steel wire was drawn through the right quadrant of the maxillary arch at 0.5 mm/min for 5 min. The SFF and KFF were measured with a mechanical testing machine and statistical analyses were performed. **Results:** Four different categories of SFF and KFF were observed among all groups (all $p < 0.001$). Group 1 demonstrated the highest SFF and KFF; groups 4 and 3 were second and third highest, respectively. The fourth category included groups 2, 5, and 6. Placing PSLBs on the MXPT resulted in significant SFF and KFF reductions in cases with CBs on the MXAT, but not in cases with ASLBs on the MXAT. **Conclusions:** These data might aid in the development of a hybrid bracket system that enables low-friction sliding of an archwire through the MXPT. [Korean J Orthod 2016;46(2):73-80]

Key words: Frictional force, Hybrid bracket system, Sliding mechanics, Self-ligating brackets

Received June 3, 2015; Revised July 23, 2015; Accepted July 24, 2015.

Corresponding author: Seung-Hak Baek.

Professor, Department of Orthodontics, School of Dentistry, Dental Research Institute, Seoul National University, 101 Daehak-ro, Jongno-gu, Seoul 03080, Korea.

Tel +82-2-2072-3952 **e-mail** drwhite@unitel.co.kr

The authors report no commercial, proprietary, or financial interest in the products or companies described in this article.

© 2016 The Korean Association of Orthodontists.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

Friction between the bracket slot and archwire is one of the most important factors to be considered in sliding mechanics.^{1,2} Self-ligating brackets (SLBs) are known to produce less friction than conventional brackets (CBs).³⁻¹¹ In general, SLBs can be categorized as active type (ASLB) or passive type (PSLB) brackets.

PSLBs are known to produce less friction than ASLBs.¹²⁻¹⁵ However, Badawi et al.¹⁶ reported that ASLBs are more effective in torque expression than PSLBs, and lower frictional force might be disadvantageous to torque expression. In addition, Rinchuse and Miles¹⁷ proposed a hybrid combination of CBs or ASLBs in the anterior segment and PSLBs in the posterior segment to take advantage of these properties. Therefore, Paik et al.¹⁸ introduced a variation of the hybrid system for premolar extraction cases called hybrid sliding mechanics for low friction: a combination of CBs on the anterior teeth, PSLBs on the second premolars, and conventional tubes on the first and second molars.

Although CBs and SLBs have been widely used, few previous studies have evaluated the frictional force in hybrid combinations of CBs, ASLBs, and PSLBs associated with sliding mechanics. Therefore, the purpose of this *in vitro* study was to investigate the static (SFF) and kinetic frictional forces (KFF) in the sliding mechanics of hybrid bracket systems that place a CB or ASLB on the maxillary anterior teeth and PSLB on the maxillary posterior teeth. The null hypothesis was that there was no significant difference in SFF and KFF in sliding mechanics between the thoroughbred and hybrid bracket groups.

MATERIALS AND METHODS

Teeth and typodont system

The stereolithographically (SL)-made typodont system, which can align the dentition according to arch form and malocclusion state, was used in this study (Figure 1A).^{9,19} Using computed tomography data, a three-dimensional (3D) virtual tooth model with root and periodontal ligament (PDL) space was designed to emulate a stress-absorbing mechanism and fabricated into 3D structures using the Viper™ Pro SLA® System (3D Systems Corporation, Rock Hill, SC, USA). The PDL space was filled with Imprint™ II Garant™ Light Body Vinyl Polysiloxane Impression Material (3M ESPE, Seefeld, Germany), which effectively reproduces the mobility of human teeth. Periotest (Siemens AG, Munich, Germany) revealed normal values in the mobility of the typodont teeth.^{9,19-21}

All teeth were aligned in their ideal positions according to the Broad Arch Form (Ormco, Orange, CA, USA). For the evaluation of frictional force in sliding mechanics during extraction space closure, the maxillary first premolar was removed from the typodont (Figure 1A). When the archwire is pulled distally on one side, binding can occur on the opposite side.⁶ Therefore, to minimize the effect of binding on the opposite side caused by pulling forces, Henao and Kusy²² used half of the maxillary arch for frictional force measurement. In this study, the frictional force was measured in the upper right quadrant of the maxillary arch.

Various combinations of CBs, ASLBs, and PSLBs

The brackets tested in this study comprised one type of CB, one type of ASLB, and two types of PSLBs (Table 1). All brackets had a 0.022-inch slot.

The samples consisted of two thoroughbred types (group 1, anterior-CB + posterior-CB; group 2, anterior-

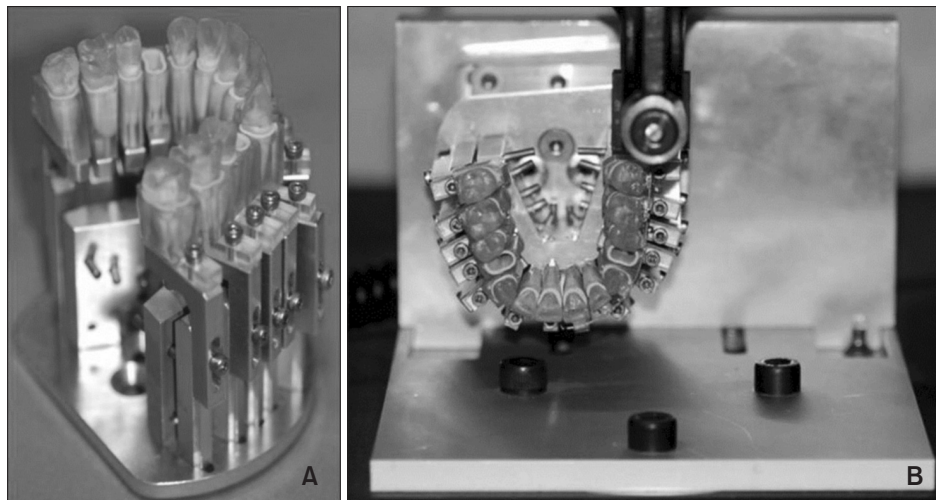


Figure 1. The stereolithographically-made typodont system. **A**, The maxillary teeth were aligned to their ideal positions according to a Broad Arch Form (Ormco). For the evaluation of frictional force in sliding mechanics during extraction space closure, the maxillary first premolar was removed from the typodont. **B**, The stereolithographically-made typodont system and testing apparatus.

Table 1. Combinations of conventional brackets, active self-ligating brackets, and passive self-ligating brackets

| Type | Group | Maxillary anterior teeth (central incisor, lateral incisor, and canine) | | Maxillary posterior teeth (second premolar, first molar, and second molar) | |
|---------------------------------|-------|--|---|---|---|
| | | Central incisor to canine | Second premolar | First molar | Second molar |
| Thoroughbred | | | | | |
| CB | 1 | CB (ceramic bracket / metal slot; Clarity, 3M Unitek) | CB (ceramic bracket / metal slot; Clarity, 3M Unitek) | Conventional convertible single tube (metal tube, 3M Unitek) | Conventional single tube (metal tube, 3M Unitek) |
| ASLB | 2 | ASLB (ceramic bracket / ceramic slot; In-Ovation C, GAC) | ASLB (ceramic bracket / ceramic slot; In-Ovation C, GAC) | Conventional convertible single tube (metal tube, GAC) | Conventional single tube (metal tube, GAC) |
| Hybrid 1 (anterior + posterior) | | | | | |
| CB + PSLB type 1 | 3 | CB (ceramic bracket / metal slot; Clarity, 3M Unitek) | PSLB type 1 (metal bracket / metal slot; Damon Q, Ormco) | PSLB type 1 (metal bracket / metal slot; Damon Q, Ormco) | Conventional single tube (metal tube; Ormco) |
| CB + PSLB type 2 | 4 | CB (ceramic bracket / metal slot; Clarity, 3M Unitek) | PSLB type 2 (ceramic bracket / metal slot; Clarity SL, 3M Unitek) | PSLB type 2 (metal bracket / metal slot; SmartClip, 3M Unitek) | Conventional single tube (metal tube, 3M Unitek) |
| Hybrid 2 (anterior + posterior) | | | | | |
| ASLB + PSLB type 1 | 5 | ASLB (ceramic bracket / ceramic slot; In-Ovation C, GAC) | PSLB type 1 (metal bracket / metal slot; Damon Q, Ormco) | PSLB type 1 (metal bracket / metal slot; Damon Q, Ormco) | Conventional single tube (metal tube; Ormco) |
| ASLB + PSLB type 2 | 6 | ASLB (ceramic bracket / ceramic slot; In-Ovation C, GAC) | PSLB type 2 (ceramic bracket / metal slot; Clarity SL, 3M Unitek) | PSLB type 2 (metal bracket / metal slot; SmartClip, 3M Unitek) | Conventional single tube (metal tube; 3M Unitek) |

CB, Conventional bracket; ASLB, active self-ligating bracket; PSLB, passive self-ligating bracket.
3M Unitek, Monrovia, CA, USA; GAC, Dentsply Corp., York, PA, USA; Ormco, Orange, CA, USA.

ASLB + posterior-ASLB) and four hybrid types (group 3, anterior-CB + posterior-PSLB-type 1; group 4, anterior-CB + posterior-PSLB-type 2; group 5, anterior-ASLB + posterior-PSLB-type 1; group 6, anterior-ASLB + posterior-PSLB-type 2) ($n = 13$ per group, Table 1). The thoroughbred types (groups 1 and 2) consisted of the same type of bracket from the same production company. The hybrid types (groups 3 to 6) consisted of one type of CB or ASLB for proper torque control of the maxillary anterior teeth and two types of PSLBs for friction reduction at the maxillary posterior teeth during *en masse* retraction.

Sliding mechanics

Each bracket was bonded on the facial axis point²³ of the SL-made typodont tooth using Transbond XT (3M Unitek, Monrovia, CA, USA). While bonding the brackets, a 0.021×0.028 -inch stainless steel (SS) wire (Broad Arch Form, Ormco) was placed to align the bracket slot and molar tube and to prevent any rotation, misalignment, or improper tipping/torque of the bracket that could influence unwanted friction during measurement.^{5,9} The 0.021×0.028 -inch SS wire was then removed from the bracket slot.

To simulate sliding mechanics for *en masse* retraction, 0.019×0.025 -inch SS archwire (Broad Arch Form, Ormco) was pulled distally from the most distal tube. In this study, the archwire length was half of a full archwire with a 90° bend at the anterior end as not to slip the archwire through the brackets or tubes during testing.

For the CBs, after ligation with elastic modules (Unistick Ligatures; American Orthodontics, Sheboygan, WI, USA), a 3-minute waiting period allowed a reproducible amount of stress relaxation to occur.^{5,9,19,22,24}

Measurement of frictional force

The typodont was then attached to a custom-made metal plate that was fixed to a mechanical testing machine (Model 4466; Instron, Canton, MA, USA; Figure 1B). A custom-designed adaptor gripped the distal end of the archwire, which was extruded from the second molar tubes. A 0.019×0.025 -inch SS wire was drawn through the brackets and tubes at a speed of 0.5 mm/min for 5 min in a dry state and at room temperature.

In this experiment, each combination was tested 13 times with new wires and brackets of the same type to eliminate the influence of wear between the wire and bracket slot. A total of 78 tests were conducted. After each test, the testing machine was stopped, the wire-bracket unit was removed, and a new assembly was placed. Both SFF and KFF were calculated by the same method used in previous studies.^{5,9,19}

Statistical analysis

The sample size determination was made from a power analysis using the Sample Size Determination Program ver. 2.0.1 (Seoul National University Dental Hospital, Registration number 2007-01-122-004453, Seoul, Korea). Independent and paired *t*-tests, a one-way analysis of variance (ANOVA), and Duncan's multiple comparison test were performed in the statistical analysis.

RESULTS

Comparisons of static and kinetic frictional force (cN) in each group

There was a significant difference between SFF and KFF in the group 1, group 3, group 4, and group 5 (groups 1, 3, and 5, $p < 0.05$; group 4, $p < 0.01$; Table 2). However, the group 2 and group 6 did not exhibit a significant difference between SFF and KFF (Table 2).

Comparisons of static and kinetic frictional forces (cN) between the thoroughbred and hybrid bracket groups

When the thoroughbred groups (groups 1 and 2) were compared, the group 1 exhibited significantly higher SFF and KFF values than the group 2 (all $p < 0.001$, Table 3).

When the anterior-CB groups (groups 1, 3, and 4) were compared, the group 3 exhibited lower SFF and KFF values than the group 1 (all $p < 0.01$, Table 3). However, there was no significant difference in SFF and KFF between the group 3 and the group 4, or between the group 1 and the group 4 (Table 3).

When the anterior-ASLB groups (groups 2, 5, and 6) were compared, there was no significant difference in SFF and KFF among the group 2, group 5, and group 6 (all $p > 0.05$, Table 3).

When the overall groups (groups 1 through 6) were compared, four different categories were observed among the six groups in terms of SFF and KFF (all $p < 0.001$, Table 3). The group 1 had the highest SFF and KFF values among all groups (Table 3). The group 4 and group 3 exhibited the second and third highest values, respectively (Table 3). These findings indicate that the placement of PSLBs on the maxillary posterior teeth with CBs on the maxillary anterior teeth (groups 3 and 4) can significantly reduce SFF and KFF compared with the group 1. The fourth category included the group 2, group 5, and group 6 (Table 3). This finding indicates that placing PSLBs on the maxillary posterior teeth in conjunction with ASLBs on the maxillary anterior teeth did not significantly reduce SFF and KFF more than in the ASLB thoroughbred group (group 2).

Table 2. Comparisons of static and kinetic frictional forces (cN) in each group

| Type | Group (n = 13/group) | Static frictional force | Kinetic frictional force | p-value |
|---------------------------------|-------------------------|-------------------------|--------------------------|---------------------|
| Thoroughbred | | | | |
| CB | 1 | 1,018.77 ± 280.06 | 955.45 ± 209.64 | 0.0172* |
| ASLB | 2 | 466.08 ± 155.31 | 461.46 ± 150.27 | 0.3657 |
| Hybrid 1 (anterior + posterior) | | | | |
| CB + PSLB type 1 | 3 | 691.38 ± 129.78 | 677.79 ± 125.61 | 0.0408* |
| CB + PSLB type 2 | 4 | 860.62 ± 265.29 | 818.53 ± 225.96 | 0.0056 [†] |
| Hybrid 2 (anterior + posterior) | | | | |
| ASLB + PSLB type 1 | 5 | 453.85 ± 79.44 | 447.38 ± 73.92 | 0.0185* |
| ASLB + PSLB type 2 | 6 | 414.54 ± 168.47 | 410.81 ± 147.45 | 0.6239 |

Values are presented as mean ± standard deviation.

A paired *t*-test was performed.

CB, Conventional bracket; ASLB, active self-ligating bracket; PSLB, passive self-ligating bracket.

**p* < 0.05, [†]*p* < 0.01.

Table 3. Comparisons of static and kinetic frictional forces (cN) between the thoroughbred bracket and hybrid bracket groups

| Combination | Group (n = 13/ group) | Static frictional force | | Kinetic frictional force | |
|---------------------|-----------------------------|-------------------------|------------------------------------|--------------------------|------------------------------------|
| | | p-value | Difference within tested groups | p-value | Difference within tested groups |
| Thoroughbred group | 1, 2 | < 0.001 [§] | 1 > 2* | < 0.001 [§] | 1 > 2* |
| Anterior CB group | 1 , 3, 4 | 0.0045 [†] | (3, 4) < (4, 1) [†] | 0.0032 [†] | (3, 4) < (4, 1) [†] |
| Anterior ASLB group | 2 , 5, 6 | 0.6222 | NS [†] | 0.5900 | NS [†] |
| Overall group | 1 to 6 | < 0.001 [§] | (6, 5, 2) < 3 < 4 < 1 [†] | < 0.001 [§] | (6, 5, 2) < 3 < 4 < 1 [†] |

CB, Conventional bracket; ASLB, active self-ligating bracket; NS, not significant.

*An independent *t*-test was performed.

[†]A one-way ANOVA was performed and the results were verified with Duncan's multiple comparison test.

[§]*p* < 0.01, [§]*p* < 0.001.

^{||}The control groups for the Anterior-CB and Anterior-ASLB groups.

DISCUSSION

There has been consistent agreement that SLBs exhibit lower friction than CBs when coupled with small round archwires.^{3,5,9,22,25,26} However, for large rectangular archwires, there seems to be controversy. Henao and Kusy^{22,24} insisted that the frictional force of SLBs coupled with large rectangular archwires was not lower than that of CBs. In a systemic review, Ehsani et al.²⁵ claimed there was no sufficient evidence that SLBs with large rectangular wires produced lower frictional forces than CBs in the presence of tipping and/or torque or in arches with considerable malocclusion. Ehsani et al.²⁵ explained that rectangular wires increased frictional force, even in SLBs, because filling the bracket slots with heavy rectangular wires might minimize differences between the SLBs and CBs.

ASLBs are known to be more effective than PSLBs in

torque expression.¹⁶ However, there are still some controversies surrounding this issue. For example, Major et al.²⁷ reported that the torque plays in ASLBs and PSLBs were virtually indistinguishable and that there was no significant difference in torque expression from a clinical perspective at angles of twist smaller than 24°. In addition, Brauchli et al.²⁸ claimed that the influence of the ligature method (conventional ligation, active self-ligation, or passive self-ligation) on torque expression was minimal and that slot dimensions were more important in the transmission of torque. Therefore, it is necessary to investigate the torque expression of SLBs with more sophisticated methodology.

To accurately measure the frictional force of SLBs and CBs with large rectangular wires, the experimental conditions should be similar to a clinical situation for *en masse* retraction. Therefore, the brackets must be aligned using 0.021 × 0.028-inch SS wire to avoid improper

rotation, in-and-out, tipping, and torque that could result in unwanted friction during measurements.^{5,9,29}

Numerous studies have evaluated the frictional force using a rectangular wire in one or several brackets in a straight form.^{4,7,10,11,15,30,31} However, it would be better to place the brackets according to a specific arch form to investigate the effect of curvature on frictional properties. Therefore, in this study, the SL-made typodont system, which can align the dentition according to arch form and malocclusion state, was used.

In this study, the CB thoroughbred group (group 1) showed significantly higher SFF and KFF values than the ASLB thoroughbred group (group 2) (1,018.8 cN vs. 466.1 cN for SFF; 955.5 cN vs. 461.5 cN for KFF; all $p < 0.001$, Tables 2 and 3). This result is consistent with those of previous studies.^{5,12-15,24,26,31} The finding that the anterior-CB + posterior-PSLB-type 2 group (group 4) and anterior-CB + posterior-PSLB-type 1 group (group 3) exhibited the second and third highest SFF and KFF values (860.6 cN and 818.5 cN for group 4; 691.4 cN and 677.8 cN for group 3; Tables 2 and 3) seemed to result from differences in the brackets. The posterior-PSLB-type 1 and posterior-PSLB-type 2 groups had different mesiodistal widths of the brackets and tubes (in the maxillary second premolars, first molars, and second molars), bracket designs (sliding door vs. clip on the maxillary second premolars and first molars), bracketslot material compositions (metal bracket and metal slot vs. ceramic bracket and metal slot in the maxillary second premolars), and bracket slot surface roughness (Table 1). Therefore, further studies are necessary to consider these

characteristics in the evaluation of frictional forces.

The reason that there was no significant difference in SFF and KFF among the ASLB thoroughbred group (group 2), anterior-ASLB + posterior-PSLB-type 1 group (group 5), and anterior-ASLB + posterior-PSLB-type 2 group (group 6) (466.1 cN, 453.9 cN, and 414.5 for SFF; 461.5 cN, 447.4 cN, and 410.8 cN for KFF, all $p > 0.05$; Tables 2 and 3) was likely because the ASLB already has a smaller frictional force than the CB. Since the CB thoroughbred group (group 1) resulted in significantly higher friction than the other groups (Tables 2 and 3), a bracket change from a CB to a PSLB on the posterior teeth could significantly reduce friction (−31.2% in group 3 and −15.5% in group 4 for SFF; −29.1% in group 3 and −14.3% in group 4 for KFF compared to group 1; all $p < 0.01$; Figure 2). However, the frictional values of the ASLB thoroughbred group (group 2) were lower than those in the CB thoroughbred group (group 1) (Tables 2 and 3). Therefore, a bracket change from an ASLB to a PSLB on the posterior teeth may not result in a significant reduction in friction (−2.6% in group 3 and −11.1% in group 4 for SFF; −3.1% in group 3 and −11.0% in group 4 for KFF compared with group 1; all $p > 0.05$; Figure 2). In summary, the type of hybrid bracket system placed on the maxillary anterior and posterior teeth (CB-PSLB or ASLB-PSLB) can affect the degrees of reduction in SFF and KFF compared with a thoroughbred bracket system (CB or ASLB).

The finding that the anterior-CB + posterior-PSLB-type 1 group (group 3) exhibited lower SFF and KFF values than the CB thoroughbred group (group 1) (all $p < 0.01$,

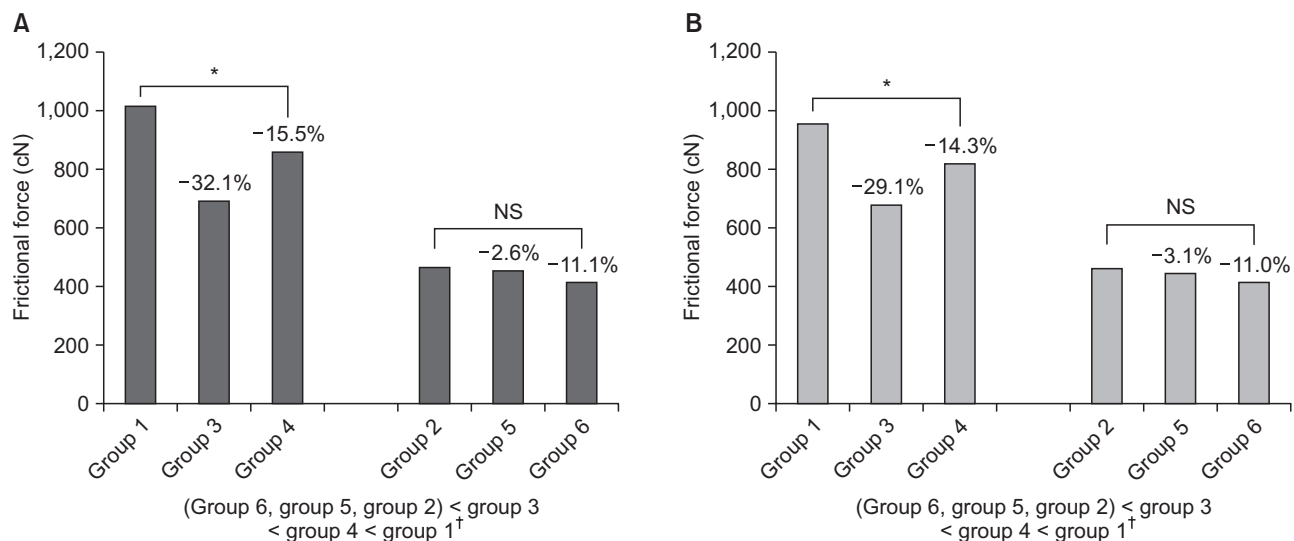


Figure 2. Comparisons of frictional force (cN) between groups 1, 3, and 4 and between groups 2, 5, and 6. **A**, Static frictional force; **B**, kinetic frictional force. A one-way analysis of variance (ANOVA) was performed and the results were verified with Duncan's multiple comparison test.

* $p < 0.01$, [†] $p < 0.001$.

Tables 2 and 3) might be similar to a case report by Paik et al.,¹⁸ who introduced hybrid sliding mechanics for low friction (a combination of CBs on the anterior teeth, PSLBs on the second premolars, and conventional tubes on the first and second molars).

In the near future, hybrid bracket systems using CBs, ASLBs, and PSLBs can be adopted in clinics according to the orthodontist's intention. Further studies are necessary to investigate the effects of the PDL material and elastic module stress relaxation method on the level of friction. Moreover, it is necessary to consider the influence of torque on friction according to bracket type in the anterior region (CB and ASLB) with respect to bracket type in the posterior region (PSLB and ASLB).

CONCLUSION

Placing PSLBs on the maxillary posterior teeth resulted in significant reductions in SFF and KFF in cases with CBs on the maxillary anterior teeth, but not in cases with ASLBs on the maxillary anterior teeth; thus the null hypothesis was rejected.

These data might be used to guide the development of a hybrid bracket system that enables low-friction sliding of an archwire through the maxillary posterior teeth.

REFERENCES

1. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. *Am J Orthod* 1980;78:593-609.
2. Arici N, Akdeniz BS, Arici S. Comparison of the frictional characteristics of aesthetic orthodontic brackets measured using a modified in vitro technique. *Korean J Orthod* 2015;45:29-37.
3. Shivapuja PK, Berger J. A comparative study of conventional ligation and self-ligation bracket systems. *Am J Orthod Dentofacial Orthop* 1994;106:472-80.
4. Budd S, Daskalogiannakis J, Tompson BD. A study of the frictional characteristics of four commercially available self-ligating bracket systems. *Eur J Orthod* 2008;30:645-53.
5. 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.
6. Krishnan M, Kalathil S, Abraham KM. Comparative evaluation of frictional forces in active and passive self-ligating brackets with various archwire alloys. *Am J Orthod Dentofacial Orthop* 2009;136:675-82.
7. 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.
8. Lee SM, Hwang CJ. A comparative study of frictional force in self-ligating brackets according to the bracket-archwire angulation, bracket material, and wire type. *Korean J Orthod* 2015;45:13-9.
9. 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.
10. Brauchli LM, Senn C, Wichelhaus A. Active and passive self-ligation-a myth? *Angle Orthod* 2011;81:312-8.
11. Huang TH, Luk HS, Hsu YC, 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.
12. Pizzoni L, Ravnholt G, Melsen B. Frictional forces related to self-ligating brackets. *Eur J Orthod* 1998;20:283-91.
13. Thorstenson GA, Kusy RP. Resistance to sliding of orthodontic brackets with bumps in the slot floors and walls: effects of second-order angulation. *Dent Mater* 2004;20:881-92.
14. Hain M, Dhoptkar A, Rock P. A comparison of different ligation methods on friction. *Am J Orthod Dentofacial Orthop* 2006;130:666-70.
15. Stefanos S, Secchi AG, Coby G, Tanna N, Mante FK. Friction between various self-ligating brackets and archwire couples during sliding mechanics. *Am J Orthod Dentofacial Orthop* 2010;138:463-7.
16. Badawi HM, Toogood RW, Carey JP, Heo G, Major PW. Torque expression of self-ligating brackets. *Am J Orthod Dentofacial Orthop* 2008;133:721-8.
17. Rinchuse DJ, Miles PG. Self-ligating brackets: present and future. *Am J Orthod Dentofacial Orthop* 2007;132:216-22.
18. Paik CH, Ahn HW, Yang IH, Baek SH. Low-friction space closure with a hybrid bracket-tube system. *J Clin Orthod* 2010;44:623-7; quiz 622.
19. 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.
20. Nakago T, Mitani S, Hijiya H, Hattori T, Nakagawa Y. Determination of the tooth mobility change during the orthodontic tooth movement studied by means of Periotest and MIMD (the mechanical impedance measuring device for the periodontal tissue). *Am J Orthod Dentofacial Orthop* 1994;105:92-6.
21. Tanaka E, Ueki K, Kikuzaki M, Yamada E, Takeuchi M, Dalla-Bona D, et al. Longitudinal measurements

- of tooth mobility during orthodontic treatment using a periostat. *Angle Orthod* 2005;75:101-5.
22. Henao SP, Kusy RP. Evaluation of the frictional resistance of conventional and self-ligating bracket designs using standardized archwires and dental typodonts. *Angle Orthod* 2004;74:202-11.
23. Andrews LF. The six keys to normal occlusion. *Am J Orthod* 1972;62:296-309.
24. Henao SP, Kusy RP. Frictional evaluations of dental typodont models using four self-ligating designs and a conventional design. *Angle Orthod* 2005;75:75-85.
25. Ehsani S, Mandich MA, El-Bialy TH, Flores-Mir C. Frictional resistance in self-ligating orthodontic brackets and conventionally ligated brackets. A systematic review. *Angle Orthod* 2009;79:592-601.
26. Franchi L, Baccetti T, Camporesi M, Barbato E. Forces released during sliding mechanics with passive self-ligating brackets or nonconventional elastomeric ligatures. *Am J Orthod Dentofacial Orthop* 2008;133:87-90.
27. Major TW, Carey JP, Nobes DS, Heo G, Major PW. Mechanical effects of third-order movement in self-ligated brackets by the measurement of torque expression. *Am J Orthod Dentofacial Orthop* 2011;139:e31-44.
28. Brauchli LM, Steineck M, Wichelhaus A. Active and passive self-ligation: a myth? Part 1: torque control. *Angle Orthod* 2012;82:663-9.
29. 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.
30. 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.
31. Oliver CL, Daskalogiannakis J, Thompson BD. Archwire depth is a significant parameter in the frictional resistance of active and interactive, but not passive, self-ligating brackets. *Angle Orthod* 2011;81:1036-44.