Original Article

Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion: Part 2. Elastic ligation

Jonathan Fok[a]; Roger W. Toogood[b]; Hisham Badawi[c]; Jason P. Carey[b]; Paul W. Major[d]

ABSTRACT

Objective: To better understand the mechanics of bracket/archwire interaction through analysis of force and couple distribution along the maxillary arch using elastic ligation and to compare these results with passive ligation.

Materials and Methods: An orthodontic simulator was used to study a high canine malocclusion. Force and couple distributions produced by elastic ligation and round wire were measured. Forces and couples were referenced to the center of resistance of each tooth. Tests were repeated for 12 bracket sets with 12 wires per set. Data were compared with those derived from similar tests for passive ligation.

Results: Propagation of the force/couple systems around the arch using elastic ligation was extensive. Elastic ligation produced significantly more resistance to sliding, contributing to higher forces and couples at the center of resistance than were observed for passive ligation.

Conclusions: The results of this study suggest some potential mechanical advantages of passive over elastic ligation. In particular, limited propagation around the arch in passive ligation reduces the occurrence of unwanted force/couple systems compared with elastic ligation. These advantages may not transfer to a clinical setting because of the conditions of the tests; additional testing would be required to determine whether these advantages can be generalized. (*Angle Orthod.* 2011;81:960–965.)

KEY WORDS: Orthodontic brackets; Orthodontics; Orthodontic appliance design; Elastic ligation

INTRODUCTION

The emergence of new ligation systems and wire designs presents the practitioner with the question of which type of appliance results in optimum treatment outcomes. Three main ligation systems are in common use (active and passive self-ligation and conventional elastic ligation). Although some investigation into the behavior of these different systems has been conducted,[1–5] the fundamental mechanics of these systems for continuous archwires has not been explored in detail. Hence debate continues as to the mechanical advantages of one ligation system over another. Because orthodontic treatment is based fundamentally on application of force/couple systems, an improved understanding of the mechanics of ligation for various bracket systems is desired.

The orthodontic simulator (OSIM)[6] was developed to quantify the force/couple systems in continuous arch mechanics. The force and moment measurement capabilities of the OSIM were previously demonstrated by Badawi et al.[7,8] A previous paper reported on the forces and couples produced when passive ligation is used in the case of an idealized high canine malocclusion.[9]

The present paper builds on previous studies by analyzing how elastic ligation affects the forces and couples exerted by the wire during the same idealized correction and performs a side-by-side comparison of the two ligation methods.

[a] Research Associate, Department of Dentistry, University of Alberta, Edmonton, Canada.

[b] Associate Professor, Faculty of Engineering, University of Alberta, Edmonton, Canada.

[c] Associate Professor, Department of Dentistry, University of Alberta, Edmonton, Canada.

[d] Professor and Chair, Department of Dentistry, University of Alberta, Edmonton, Canada.

Corresponding author: Dr Paul W. Major, Room 3036, Dentistry/Pharmacy Centre, University of Alberta, Edmonton, Alberta T6G 2N8, Canada
(e-mail: major@ualberta.ca).

Accepted: May 2011. Submitted: January 2011.
Published Online: 14 June 2011

 DOI: 10.2319/012011-41.1

MATERIALS AND METHODS

The testing procedure, coordinate systems, and data transformations were discussed in Part 1 of this paper.[9] As in the previous paper, all force/couple data are referenced to the center of resistance (CR) of each tooth. This allows independent consideration of the translation and rotation of each tooth under applied loads.

Tests used 0.014-inch round copper-nickel-titanium (CuNiTi) wires, which are part of the Damon series (Ormco, Orange, Calif). To ensure testing consistency between the passive and elastic ligation tests, the same brackets (Damon 3MX series) with the gates left open and elastics applied across the face were used to represent elastic ligation systems. Therefore slot geometry (length and width), which is critical to issues such as binding, was the same as used in Part 1 of this study.[9] To maintain consistent elastic prestress, elastics are applied to the bracket face through the use of a Straight Shooter Ligature Gun (TP Orthodontics, La Porte, Ind). A sample size of 12 Damon 3MX bracket sets was utilized, along with 12 new wires per bracket set, for a total of 144 tests.

Setup of the test apparatus and engagement of the wire followed the identical procedure used in Part 1 of this study.[9] In fact, the two bracket systems were tested at the same time with a randomized order of selecting passive or elastic ligation. For both ligation techniques, teeth 1–6 and 2–6 utilized passive ligation throughout all testing.

Statistical analysis was performed utilizing the Statistical Package for the Social Sciences (SPSS; SPSS Inc, Chicago, Ill) while graphical visualization of the data was compiled using Microsoft Excel (Microsoft, Redmond, Wash), as well as Pro/ENGINEER (PTC, Needham, Wash). Tests of significant difference between passive and elastic ligation were done using both the Tamhane test and the Wilks' lambda multivariate test. A level of significance value of .05 was utilized for both tests.

RESULTS

Data are presented in the same two representations as used by Fok et al.[9] with averaged data from all 144 tests. The first representation shows one of the force/couple components on all teeth around the arch. These figures show results for both the current elastic ligation tests and the passive ligation tests used in Part 1[9] for comparison. The second representation shows a view of all force/couple systems acting simultaneously for a particular value of the high canine position for the elastic tests only (similar figures for passive tests are shown in Part 1[9]).

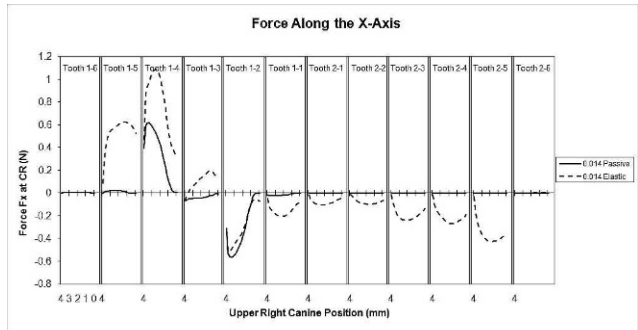


Figure 1. Force component F_X* for all teeth around the arch for elastic and passive ligation.

Figures 1, 2, and 3 display average F_X*, F_Y*, and F_Z* forces, respectively, for all teeth around the arch. Each subfigure represents the force history on a single tooth as the high canine is lowered from its initial position (+4 mm) to the neutral plane. Only the 1–6 tooth horizontal axis is labeled with the position. Each subfigure can be considered as a single graph that shares a common vertical axis and an identical horizontal axis range.

Figures 4, 5, and 6 show average M_X*, M_Y*, and M_Z* couples, respectively, for all teeth around the arch.

The second form of data representation, more qualitative but more easily visualized, is shown in Figures 7 and 8. These show the combined force/couple data for the condition when the 1–3 tooth is in the +3 mm and +1 mm positions, respectively. The force and couple components are shown separately for clarity, although it is recognized that these occur simultaneously on each tooth. All components are positioned at the location of the CR for each tooth. The bracket and tooth shapes shown in the figures are generic and are used only for visual reference. Component values less than the indicated thresholds are not shown. In the on-line version of this paper, interactive three-dimensional models of these and other figures are available. In accordance with Tamhane and Wilks' lambda testing, all teeth save for 1–6 and 2–6 demonstrated statistically significant

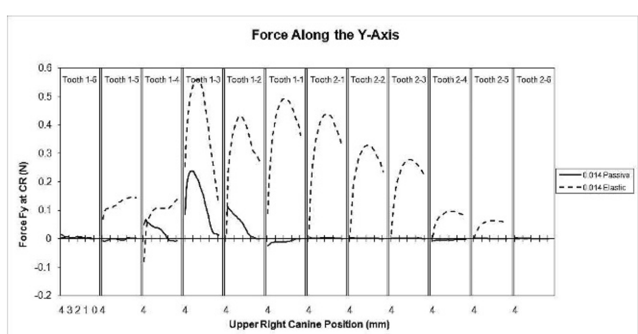


Figure 2. Force component F_Y* for elastic and passive ligation.

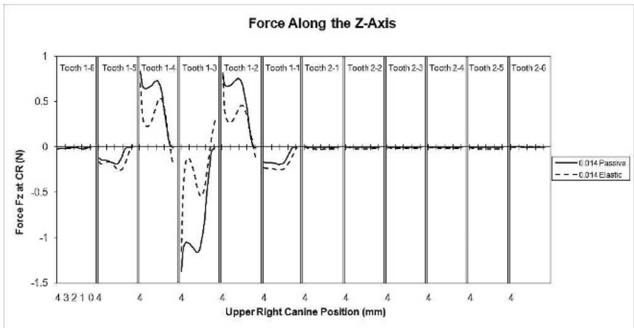


Figure 3. Force component F_Z* for elastic and passive ligation.

differences between passive and elastic ligation techniques in all principal directions at a level of $P < .05$. The sample size we used allowed for a force and moment value detection of 0.09 N and 0.4 Nmm.

DISCUSSION

The main observation about the distributions resulting from elastic ligation shown in Figures 1 through 8 is that forces and couples are generated throughout the arch. In Part 1 of this study, this was referred to as propagation of the disturbance caused by the raised 1–3. As can be seen in the figures, propagation with passive ligation extends usually only to the adjacent teeth (1–4 and 1–2), and never to the left side of the arch. With elastic ligation, however, propagation of almost all components to every tooth in the arch occurs (except 1–6 and 2–6, which, as mentioned, were passively ligated). The vertical (Fz) forces on adjacent teeth are greater with passive ligation than with elastic ligation, while forces acting on adjacent teeth for the other directions (Fx, Fy) were smaller with passive ligation.

A second major observation is that, with elastic ligation, some force and couple components do not vanish, as occurs with passive ligation, when the 1–3 is brought down to the neutral plane. Recall that in this position, OSIM was initially set prior to each test to have near-zero force/couple components. Forces and couples that do not return to zero are F_X* and F_Y*, and all the related couples M_X*, M_Y*, and M_Z*. When the 1–3 returns to the neutral plane, some deformation of the elastics that are causing these components is evident.

Forces F_X* (mesio-distal) shown in Figure 1 are caused by resistance to sliding of the wire in the bracket. In Part 1,[9] it was shown that for 1–4 and 1–2, the primary source of this resistance for much of the experiment is binding in the bracket XZ plane. Because the same wire/bracket geometry was used independent of the ligation method, the same is true here. It is noted in Figure 1 that additional resistance is present on the 1–4, which must be due to the elastics. The force components on the 1–4 and 1–2 under elastic ligation are not equal and opposite, as they were for passive ligation, and a significant nonzero mesio-distal force is present on the 1–3. Although symmetry is noted about the 1–3 in the F_X* results for passive ligation, this does not exist for the elastic case. For the remainder of the arch, the wire aligns with the slot, hence no binding occurs, and the sole contributor to F_X at the bracket is friction due to elastic ligation. Observe that this friction component exists on the entire left side of the arch for elastic ligation, where none exists for passive ligation. This is also reflected in the presence of M_X* and M_Y* couples (caused by F_X*), as discussed later.

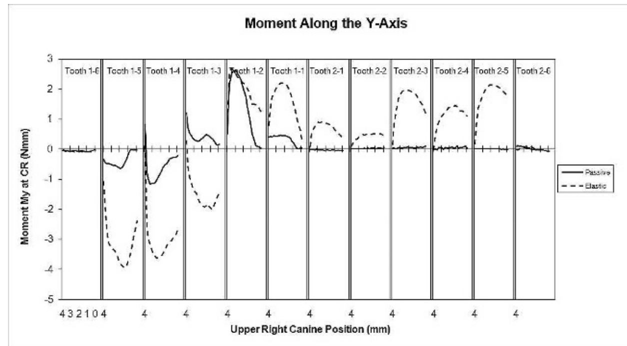


Figure 5. Couple component M_Y* for elastic and passive ligation.

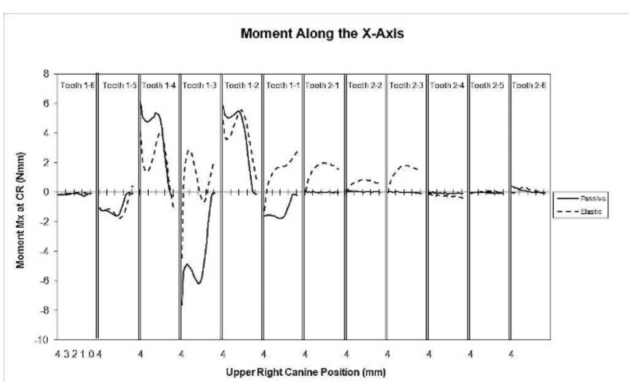


Figure 4. Couple component M_X* for elastic and passive ligation.

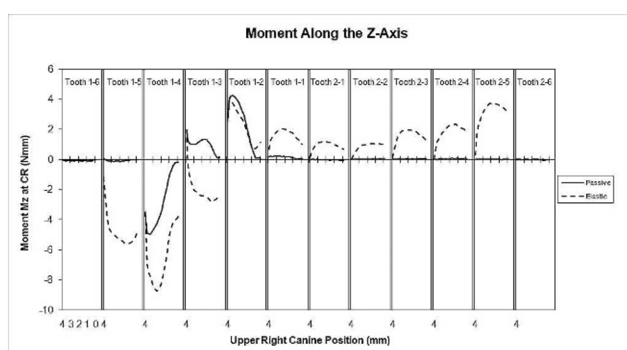
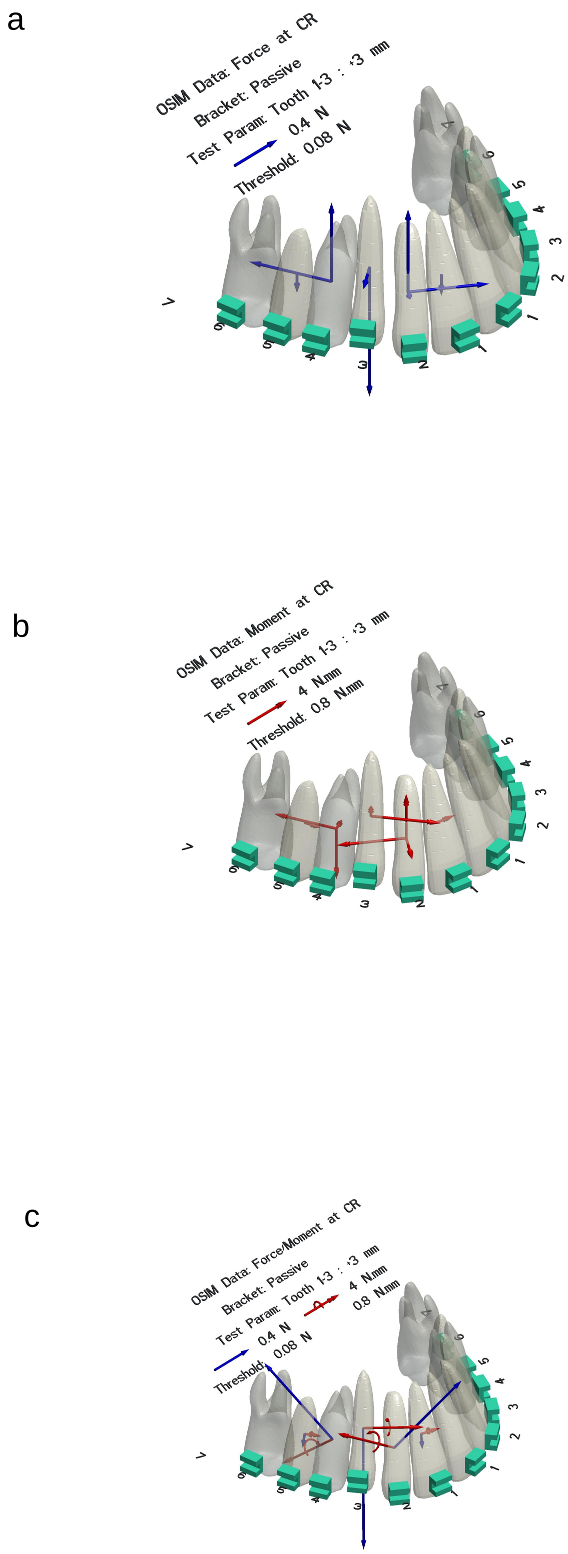


Figure 6. Couple component M_Z* for elastic and passive ligation.

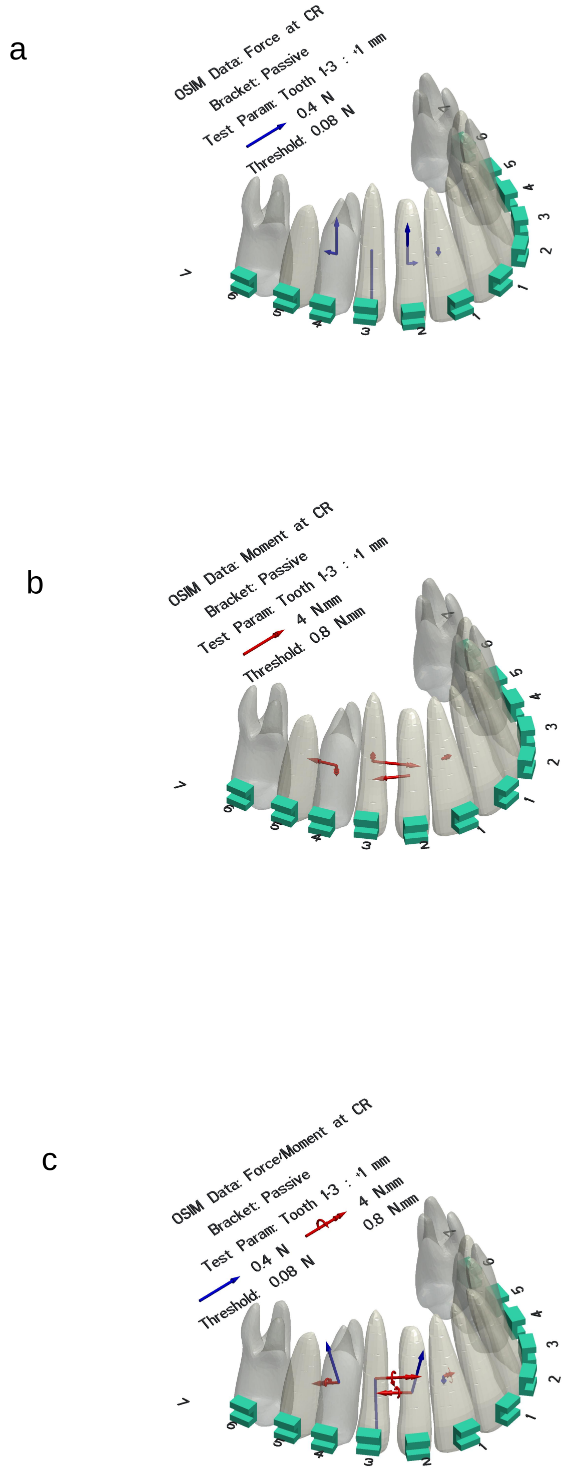


As seen is Figures 2, 7a, and 8a, all teeth along the arch using elastic ligation demonstrate the presence of buccal forces (F_Y*) throughout the experiment. Magnitudes of F_Y* for the 1–3 through to the 2–3 (where the wire curvature in the XY plane is high and more or less constant) are comparable. These forces could be associated with proclination of the teeth (note that the force F_Y* does not vanish even when the 1–3 has reached the neutral plane). These buccal forces occur only on the 1–3 and on immediately adjacent teeth for passive ligation. In elastic ligation, the wire is constantly grasped by the elastic at each bracket, which will oppose the wire sliding through the slot even if it is aligned. As the 1–3 descends, the interbracket distance decreases, and the wire, because it is partially restricted from sliding through the slot, must flex outward. This outward flexing consequently results in an increase in F_Y*. It should be noted that the magnitude of the F_Y* is considerably less than that of F_X* and F_Z*, but it still does contribute to M_X*, and the direction of F_Y* is consistently labial.

Figure 3 displays the F_Z* force pattern along the entire arch. Under elastic ligation, the magnitude of F_Z* on the 1–3, the desired force, is significantly less than that using passive ligation. This finding is contrary to the widely disseminated ''lighter force'' description of passive ligating brackets. Although this does not negate the potential benefits of self-ligation in reducing unwanted forces, it does suggest that smaller arch wires should be considered for passive self-ligation to achieve the same extrusive force on the canine. The curves demonstrate a similar S-shape, as observed and discussed at length in Part 1.[9] This shape is due to the combined effects of bending of the wire and resistance to sliding in adjacent brackets. In the case of passive ligation, resistance to sliding is caused by binding in the 1–4 and the 1–2. In the case of elastic ligation, using the same geometry of bracket results in the same amount of binding in these teeth plus an added contribution to the sliding resistance caused by traction of the elastic on the wire itself. This added resistance causes an increase in the F_X on the wire at the bracket. Following the argument presented in Part 1,[9] this produces a significant drop in F_Z*. It was postulated in Part 1[9] that sufficient resistance to sliding in the 1–4 and the 1–2 could decrease the F_Z* on the 1–3 to near zero. This is what is observed at around the +3 mm mark using elastic ligation. Note that this is accompanied by the peak values in F_X*.

←

Figure 7. (a) Force, (b) couple, and (c) total components on CR for right canine +1 mm from neutral plane.



Because the test uses round wire, M_X at the bracket is minimized. Only two contributors to M_X^* are present then: forces along the bracket Y- and Z-axes. The distribution of moment loads along the wire can be seen in Figure 5. The M_X^* curves mimic the F_Z^* and F_Y^* curves in regions where each is dominant. Note the sense that all the M_X^* couples (except for 1–5) for elastic ligation are in a direction that would cause proclination of the teeth. In a clinical setting, these couples could be compensated by generation of a countermoment M_X on the bracket using rectangular wire.

Couple M_Y^* at the CR is dominated by F_X^* forces. Therefore, although these couples are essentially zero for passive ligation, elastic ligation produces significant couples on all teeth around the arch. The moment distributions shown in Figure 6 are similar in shape to the force distributions and show an initial buildup related to developing resistance to sliding through the elastics before diminishing. Note that even when the 1–3 returns to the neutral plane, some residual forces in the brackets cause moments on the teeth that would produce mesio-distal tipping.

M_Z^* causes rotation about the long axis of the tooth. It is primarily caused by F_X^*, and therefore the curves have similar shapes (Figure 6). As in the case of M_Y^*, for elastic ligation the couple appears throughout the arch. Except for tooth 1–2, where they are similar, magnitudes of M_Z^* are significantly higher with elastic ligation. On the left side of the arch, no couple is felt with passive ligation.

Figures 7 and 8 show the force/couple systems for two different heights of the 1–3. Propagation of components around the arch is clearly indicated. Standard deviations for forces/moments acting along the entire arch were not included for clarity purposes, as plotting the standard deviation for all 12 teeth would result in significant graphic cluttering and render the plot illegible. It should be noted, however, that the standard deviation for passive ligation brackets is not the same for elastic ligation systems; the latter system incurs a significantly higher standard deviation.

As discussed in Part 1,[9] the tests performed here did not contain several factors that exist in an oral environment. These include tooth-to-tooth contact, simulation of the alveolar complex (primarily compliance of the periodontal ligament), and the effects of saliva. These factors would affect the mechanics of the force/couple generation and propagation around the wire. Another factor not included was the random/irregular disturbances that would occur, for example,

←

Figure 8. (a) Force, (b) couple, and (c) total components on CR for right canine +3 mm from neutral plane.

by chewing. It is conjectured that these would have an effect on resistance to sliding by causing a release in binding or traction of elastic on the wire.[10] Based on the discussion here, this would have a possibly major direct effect on the F_X* components, and therefore also on M_Y* and M_Z*, but also on other components as well. It is not known how important this effect might be, and this is the subject of further study with OSIM. Finally, the tests were performed in a dry environment over a short period of time with new elastics. Therefore, the effects of aging of the elastomer in the oral environment are not included here. This aging would produce relaxation in the elastic modulus and consequent reduction in the traction forces holding the wire. This would also result in a reduction in resistance to sliding.

It is noted that conventional elastic ligation brackets were simulated here using passive ligation brackets with the gates left open. This was done to ensure that the same wire/bracket geometry and degree of binding would be present in both ligation cases, and therefore the only difference would be the presence of the elastic and the traction it produces directly on the wire. It is possible that conventional tie wing brackets could produce different force diagrams as the result of differences in bracket geometry and the specifics of ligation geometry (this is how and where the elastic contacts the wire and the forces it induces between the wire and the slot walls).

This study shares the same limitations as that described in Part 1 concerning the assumed location of the CR. This position is not known with great precision, and patient-specific variation of the center of resistance has not been explored.

Because only one type of malocclusion was studied, the indicated potential advantages of passive ligation cannot be generalized to other types of orthodontic malocclusions. Consequently, this study should not be used to define the general advantages or disadvantages of one ligation system over another. To address these questions, future studies would include the use of different bracket systems of the same ligation type to determine the differences between brands, materials, geometries, and manufacturing processes. Further study is warranted of different malocclusion geometries, while factoring in additional variables associated with the oral environment as discussed earlier.

CONCLUSIONS

- Conventional elastic brackets, in the absence of other factors such as chewing, generally restrict wire movement, which causes significant differences in applied forces and couples. Furthermore, again in the absence of other factors, elastic ligation results in propagation of forces and couples around the arch, which, again, depending on desired treatment outcome, could be undesired.
- Evaluation of the mechanics of the bracket systems studied provides insight as to the natural behavior of passive and elastic ligation systems. However, numerous additional factors must be considered or included in the experiments to completely capture effects occurring in the oral environment.

ACKNOWLEDGMENT

The authors thank Ormco for kindly donating all testing materials.

REFERENCES

1. Fansa M, Keilig L, Reimann S, Jäger A, Bourauel C. The leveling effectiveness of self-ligating and conventional brackets for complex tooth malalignment. *J Orofac Orthop*. 2009;70:285–296.
2. Chen J, Isikbay SC, Brizendine EJ. Quantification of three-dimensional orthodontic force systems of T-loop archwires. *Angle Orthod*. 2010;80:566–570.
3. Franchi L, Baccetti T, Camporesi M, Giuntini V. Forces released by nonconventional bracket or ligature systems during alignment of buccally displaced teeth. *Am J Orthod Dentofacial Orthop*. 2009;136:316.e1–e6, discussion 316–317.
4. Sifakakis I, Pandis N, Makou M, Eliades T, Bourauel C. Forces and moments on posterior teeth generated by incisor intrusion biomechanics. *Ortho Craniofac Res*. 2009;12:305–311.
5. Pandis N, Eliades T, Partowi S, Bourauel C. Forces exerted by conventional and self-ligating brackets during simulated first- and second-order corrections. *Am J Orthod Dentofacial Orthop*. 2008;133:738–742.
6. Toogood RW, Badawi HM, Carey J, Farys A, Malis I, Chen E, Brenet L, Major P. Design of the orthodontic simulator (OSIM). Presented at: CSME Forum; June 7–9, 2010; Victoria, British Columbia, Canada.
7. Badawi HM, Toogood RW, Carey JP, Heo G, Major PW. Three dimensional orthodontic force measurements. *Am J Orthod Dentofacial Orthop*. 2009;136:518–528.
8. Badawi HM. *The Use of Multi-axis Force Transducers for Orthodontic Force and Moment Identification* [PhD thesis]. Edmonton, Alberta, Canada: University of Alberta; 2009.
9. Fok J, Toogood RW, Badawi HM, Carey JP, Major PW. Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion. Part 1. Passive ligation systems. *Angle Orthod*. Submitted January 2011.
10. O'Reilly D, Dowling PA, Lagerstrom L, Swartz M. An ex-vivo investigation into the effect of bracket displacement on the resistance to sliding. *Br J Orthod*. 1999;26:219–227.