Original Article

Influence of second-order bracket-archwire misalignments on loads generated during third-order archwire rotation in orthodontic treatment

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ABSTRACT

Objective: To investigate the influence of a rotational second-order bracket-archwire misalignment on the loads generated during third-order torque procedures. Specifically, torque in the second- and third-order directions was considered.

Materials and Methods: An orthodontic torque simulator (OTS) was used to simulate the third-order torque between Damon Q brackets and 0.019 $\times$ 0.025-inch stainless steel archwires. Second-order misalignments were introduced in 0.5° increments from a neutral position, 0.0°, up to 3.0° of misalignment. A sample size of 30 brackets was used for each misalignment. The archwire was then rotated in the OTS from its neutral position up to 30° in 3° increments and then unloaded in the same increments. At each position, all forces and torques were recorded. Repeated-measures analysis of variance was used to determine if the second-order misalignments significantly affected torque values in the second- and third-order directions.

Results: From statistical analysis of the experimental data, it was found that the only statistically significant differences in third-order torque between a misaligned state and the neutral position occurred for 2.5° and 3.0° of misalignment, with mean differences of 2.54 Nmm and 2.33 Nmm, respectively. In addition, in pairwise comparisons of second-order torque for each misalignment increment, statistical differences were observed in all comparisons except for 0.0° vs 0.5° and 1.5° vs 2.0°.

Conclusion: The introduction of a second-order misalignment during third-order torque simulation resulted in statistically significant differences in both second- and third-order torque response; however, the former is arguably clinically insignificant. (*Angle Orthod.* 2016;86:358–364.)

KEY WORDS: Orthodontic torque simulator; Third-order torque; Biomechanics; Orthodontics

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INTRODUCTION

The study of orthodontic loads produced during third-order rotation of an archwire engaged in a bracket is an important subject that has been considered widely in the literature.[1–9] First-, second-, and third-order rotations refer to rotation about a tooth's long axis, an axis in the buccal-lingual direction (eg, resulting in root/crown movement in the mesial-distal direction), and an axis in the mesial-distal direction (eg, resulting in root/crown movement in the buccal-lingual direction), respectively, as illustrated in Figure 1. Gmyrek et al.[1] compared plastic and metal bracket materials, and Archambault et al.[2] studied the impact of changing wire material. Major et al.[3] investigated the torque expression of different self-ligating brackets, while Major et al.[4] and Melenka et al.[7] also studied different self-ligating systems but with the addition of optical measurement techniques to measure bracket deformation. Hirai et al.[5] incorporated changes in wire size and material, bracket slot dimension, and ligation

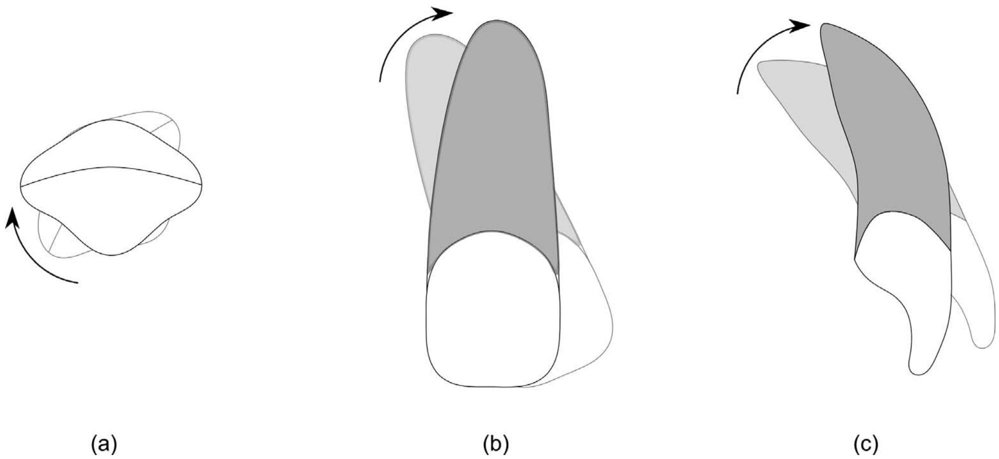

Figure 1. Illustration of tooth movement in the (a) first-order, (b) second-order, and (c) third-order directions.

method to understand how different combinations would influence treatment mechanics. Sifakakis et al.[9] also studied the impact of slot dimension on third-order torque mechanics. Finally, the use of pretorqued wires[6] and lingual brackets[8] in third-order rotation mechanics has been investigated.

While there are numerous studies considering the application of third-order torque in orthodontics, none have investigated the influence of a bracket archwire misalignment in another plane or direction. As has been well established in the literature, the physics of sliding mechanics changes dramatically with increasing second-order bracket-archwire misalignments.[10,11] In consideration of this, it would seem logical to expect that the orthodontic loads generated during archwire rotation will be influenced by various bracket-archwire misalignments. Such misalignments could include first- or second-order rotations, linear offsets in the incisal-gingival or buccal-lingual directions, or any combination of these deviations. These instances could arise as a result of tooth and/or bracket position relative to the archwire. It is essential to understand not only the additional loads generated from a bracket-archwire misalignment but also how the desired third-order torque expression is affected.

The goal of this study is to investigate how second- and third-order torque values are influenced by a second-order rotational bracket-archwire misalignment. Such a misalignment may arise clinically through the bracket being bonded with a slight rotational offset from the long axis of the tooth or if a tooth being exposed to third-order torque still has some degree of second-order rotation. Results from this study will begin to elucidate the topic of bracket-archwire misalignment during third-order torque procedures and how it may affect treatment outcomes through resulting mechanics.

MATERIALS AND METHODS

Experimental Procedure

An orthodontic torque simulator (OTS), as described in previous research[2–4,7] and illustrated in Figure 2, was used to examine the effect of a second-order bracket-archwire misalignment during third-order archwire rotation. Test samples were made by attaching Damon Q self-ligating brackets (Ormco Corporation, Orange, Calif) to the top of each dowel with LOCTITE E-60HP Hysol Epoxy adhesive (Loctite, Westlake, Ohio). The dowels had a nominal diameter of 8.90 mm and a height of 8.95 mm.

Samples were mounted in the OTS and ligated to a straight 0.019 $\times$ 0.025-inch rectangular stainless steel archwire (Ormco Corporation). A six-axis load cell (Nano17, ATI Industrial Automation, Apex, NC) along with translational and rotational stages was used to minimize preload forces and torques, which, at most, were 0.05 N and 0.35 Nmm, respectively; however, most cases were less than 0.01 N of initial force and

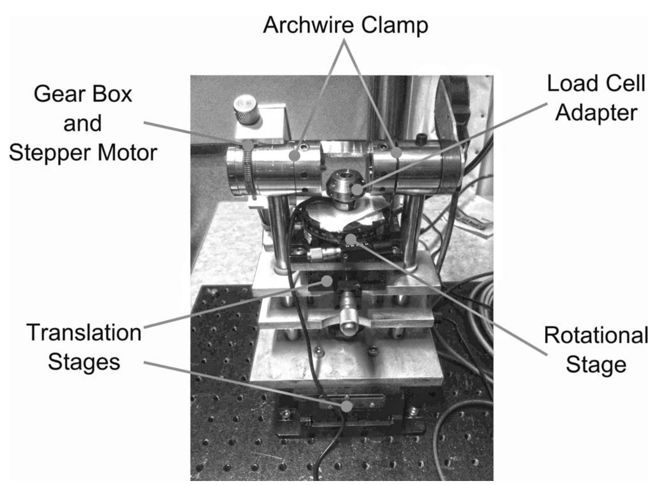

Figure 2. Orthodontic torque simulator (OTS).

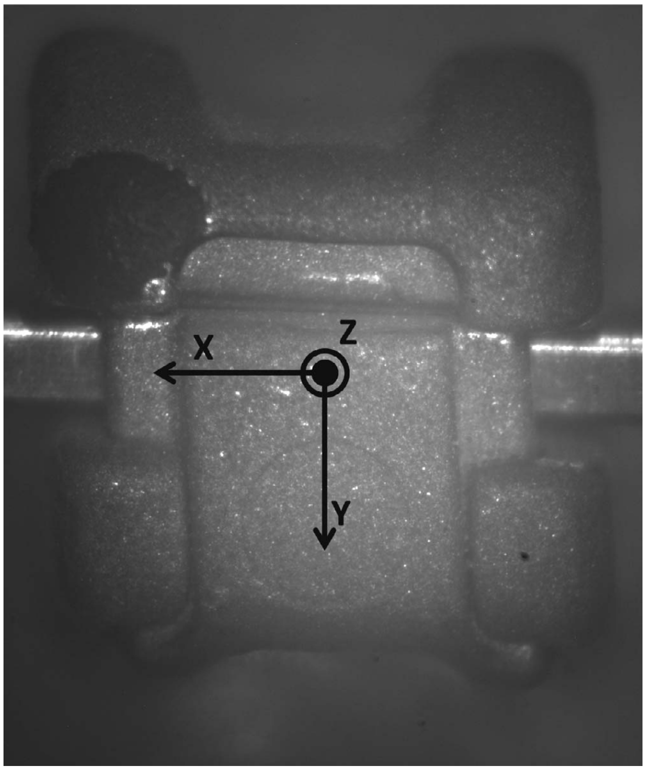

Figure 3. Orientation of the X- and Y-directions at the bracket-dowel interface with the Z-axis acting out of the page.

0.1 Nmm of initial torque. The manufacturer-specified load cell resolution for all torque values is 1/32 Nmm, and the measurement uncertainties are 1.50% and 1.75% of full-scale load in the *X*- and *Z*-directions, respectively. Misalignment was applied in the second order using a high-precision rotation mount (Thorlabs Inc, Newton, NJ) on the OTS. The rotation stage has a manufacturer-specified resolution of 5 arcmin (0.08°). Misalignments ranged from 0.0° up to 3.0° in 0.5° increments in the counterclockwise direction with respect to Figure 3. Thirty samples were tested at each misalignment angle, yielding a total sample size of 210 brackets. The archwire was rotated from the neutral position, 0°, up to 30° and back down to 0° in 3° increments. All force and torque values were recorded by the load cell at each archwire rotation interval.

The torque values were transformed from the load cell to the location of the dowel-bracket interface using the equations:

$$T_x = T_{x'}\cos(\theta) - F_{z'}\Delta y\cos(\theta) + F_{z'}\Delta x\sin(\theta) + T_{y'}\sin(\theta) + F_{y'}\Delta z\cos(\theta) - F_{x'}\Delta z\sin(\theta) \qquad (1)$$

$$T_z = T_{z'} - F_{y'}\Delta x + F_{x'}\Delta y \qquad (2)$$

where *T* represents torque (Nmm), *F* represents force (N), and Δ is the offset distance between load cell and dowel-bracket interface coordinate systems. The $X'Y'Z'$ coordinate system originates at the load cell, while the *XYZ* system has its origin at the dowel-bracket interface. θ is the rotation of the load cell and bracket with respect to the orthodontic archwire in the *XY*-plane. *X*-, *Y*-, and *Z*-directions are shown in Figure 3.

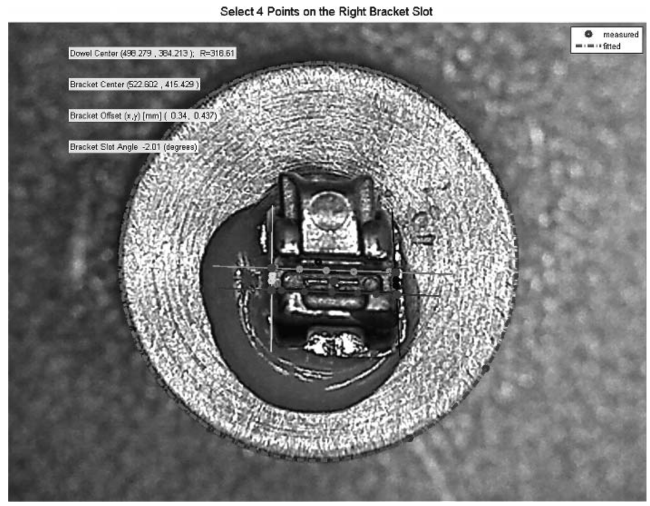

Figure 4. Sample image illustrating the bracket-dowel offset measurement; text in the upper-left corner indicates findings of the offset measurements.

Δx and Δy were found using images from a Plugable USB 2.0 Digital Microscope (Plugable, Bellevue, Wash) and an in-house–developed measurement program. The outside of the individual circular dowels was measured and then defined on the image. By knowing the actual diameter, the image could be calibrated from pixels to millimeters. The center of the bracket in the *XY*-plane was determined by selecting points along all four walls of the slot. By intersecting these lines and constructing corner-to-corner lines, the center of the bracket was approximated. With the bracket dowel and load cell being concentric, the *X*- and *Y*-direction offsets could be determined. A sample image representing this process is presented in Figure 4. Finally, Δz was determined by using a FARO Arm (FARO, Lake Mary, Fla) portable measurement device.

Statistical Analysis

Repeated-measures analysis of variance (ANOVA) statistical analysis was used to investigate the response of T_x and T_z as second-order misalignments were introduced during third-order archwire rotation. T_x values for 0° of misalignment were compared with all other misalignment increments to determine if it was affected by a second-order rotation. Conversely, when inspecting T_z, each incremental misalignment angle in the second-order direction was compared with the

Table 1. Pairwise Comparisons of Prescribed Second-Order Misalignments to the Neutral Position for T_x

	Second-Order Misalignment, °	Mean Difference, T_x, Nmm	SE	Significance	95% Confidence Interval for Difference, T_x, Nmm	
					Lower Bound	Upper Bound
Neutral second-order alignment (0.0°)	0.5	−0.59	0.66	0.376	−1.89	0.72
	1.0	0.30	0.71	0.676	−1.11	1.71
	1.5	−0.94	0.66	0.157	−2.24	0.37
	2.0	−1.09	0.72	0.134	−2.52	0.34
	2.5	−2.54	0.64	0.000	−3.81	−1.27
	3.0	−2.33	0.67	0.001	−3.65	−1.01

previous to observe if it was significantly altered by the misalignment. Both loading and unloading data were considered; however, there was no cross-comparison of data between loading and unloading phases.

While the archwire was rotated to 30° in increments of 3°, only angles up to 21° were considered for statistical analysis. First, in previous work, it was found that at 20° of rotation using Damon Q brackets and 0.019 × 0.025-inch stainless steel archwire, T_x values met or exceeded 20 Nmm.[3,4] Evidence suggests that the optimal range for producing tooth movement during third-order torque procedures is 5–20 Nmm. As such, going beyond this would be arguably clinically irrelevant. Second, in the OTS, there is an inherent backlash of approximately 1.5° that manifests in the gearing system when switching from loading to unloading phases. Analyzing data in this region would be erroneous as the system is not properly engaged. Thus, by exceeding the point of interest prior to switching phases, up to 30°, this backlash can be removed from the data. For these reasons, only data up to 21° were considered.

RESULTS

The average T_x and T_z values for each second-order misalignment increment during loading and unloading phases are plotted in Figures 5–8. In addition, the pairwise comparisons for T_x and T_z are presented in Tables 1 and 2, respectively. Graphically, it appears that there is little variation in T_x during both loading phases as the second-order misalignment increases. This is further supported by the ANOVA, which suggests that the only statistically significant mean differences of 2.54 Nmm and 2.33 Nmm occurred at second-order misalignment angles of 2.5° and 3.0°, respectively. Conversely, it was found that T_z typically differed during third-order torque simulation as the second-order misalignment was increased. From the ANOVA, the only pairs that did not show a statistically significant mean difference were 0.0° vs 0.5° and 1.5° vs 2.0°.

DISCUSSION

In comparing the third-order torque response, T_x, at the neutral position to varying levels of second-order rotational misalignment, there was no statistically significant difference until misalignments of 2.5° and 3.0° were prescribed. Using Kusy and Whitley's method of determining the critical engagement angle[11] for a 0.019 × 0.025-inch wire and a Damon Q bracket having a 0.022-inch slot and 0.110-inch width, the theoretical second-order critical angle of engagement is approximately 1.6°. Thus, not observing any significant effect of misalignment below this angle is expected. At 2.0° of second-order misalignment, one may presume a significant difference based on the theoretical angle of engagement; however, the lack of significant effect on T_x is not entirely unexpected given that the archwire and bracket would have engaged minimally at this point. In addition, manufacturing tolerances will certainly play a role in the second-order engagement of a bracket and archwire, and previous work has shown that bracket dimensions may differ from their stated size.[12]

Table 2. Pairwise Comparisons of Incremental Second-Order Misalignments for T_z

Comparison	Mean Difference, T_z, Nmm	Significance	95% Confidence Interval for Difference, T_z, Nmm	
			Lower Bound	Upper Bound
0.0° vs 0.5°	3.79	0.151	−1.40	8.98
0.5° vs 1.0°	6.84	0.019	1.16	12.53
1.0° vs 1.5°	6.43	0.027	0.74	12.12
1.5° vs 2.0°	2.30	0.433	−3.48	8.08
2.0° vs 2.5°	11.05	<0.001	5.41	16.70
2.5° vs 3.0°	7.32	0.006	2.12	12.52

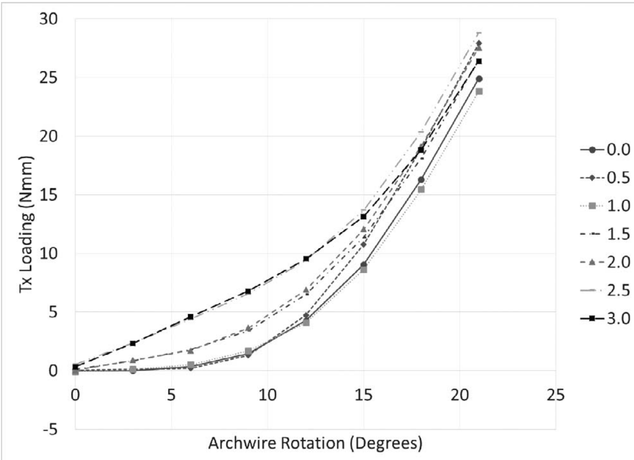

Figure 5. T_x during the loading phase of torque simulation at prescribed second-order offset angles.

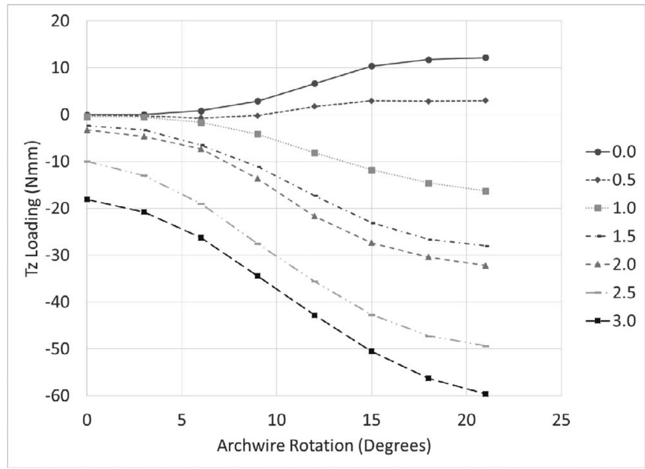

Figure 7. T_z during the loading phase of torque simulation at prescribed second-order offset angles.

When considering the magnitude of mean difference in T_x over the range of third-order rotation tested, the largest difference was 2.54 Nmm for a 2.5° misalignment. Given the desired range of torque application for orthodontic tooth movement, 5–20 Nmm, and the large variation in biological tissue properties, namely, the periodontal ligament,[13] it can be suggested that the statistical difference found is not of great significance with regard to clinical application. Graphically, primarily in Figure 5 during the loading phase, the engagement between bracket and archwire occurs at lower angles of archwire rotation for a second-order misalignment of 1.5° and greater. During the unloading phase depicted in Figure 6, the difference in T_x is pronounced at low angles of archwire rotation only for misalignments of 2.5° and 3.0°.

The discrepancy between loading and unloading phases is likely due to plastic deformation of the bracket and/or archwire that occurred at large magnitudes of T_x.[4,7] This would have resulted in larger slot dimensions and as a result less engagement between bracket and archwire for lower angles of archwire rotation. With respect to the noticeable difference between T_x curves at lower angles of archwire rotation, it is expected that as the bracket is misaligned in the second-order direction, edges of the bracket slot are moved closer to the archwire. As the archwire rotates relative to the bracket, it should make contact at lower angles of rotation than if the slot walls and wire were parallel, thus explaining the difference in T_x curves at low angles of archwire rotation.

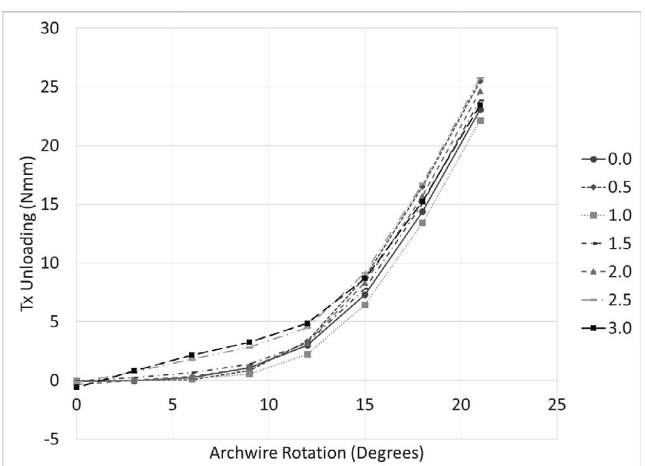

Figure 6. T_x during the unloading phase of torque simulation at prescribed second-order offset angles.

As expected, the second-order rotation of the bracket relative to the archwire had a substantial impact on the response of T_z, both initially and during archwire rotation. From Figures 7 and 8, it can be observed that for second-order offsets less than 1.5°, there was very little, if any, effect on the initial T_z value. Again, given a theoretical angle of engagement of 1.6° for this bracket-archwire pair, this result is expected. During archwire rotation, T_z magnitude increases and exhibits a plateauing trend. T_z values become increasingly negative since the counterclockwise rotation of the bracket generates a couple in the clockwise direction, which is negative based on the load cell coordinate system. It is suggested that the plateauing trend is a result of the archwire contacting more of the bracket slot closer to its center, thus contributing less to an increasing second-order torque.

From Table 2 in the pairwise comparison of incremental second-order misalignments, it can be seen that each increase in offset angle led to a statistically significant difference in T_z during third-order archwire rotation, with the exception of two pairs: 0.0° vs 0.5° and 1.5° vs 2.0°. The lack of significance in the former pair is likely due to minimal couple generated by the increase in misalignment angle. Conversely, the lack

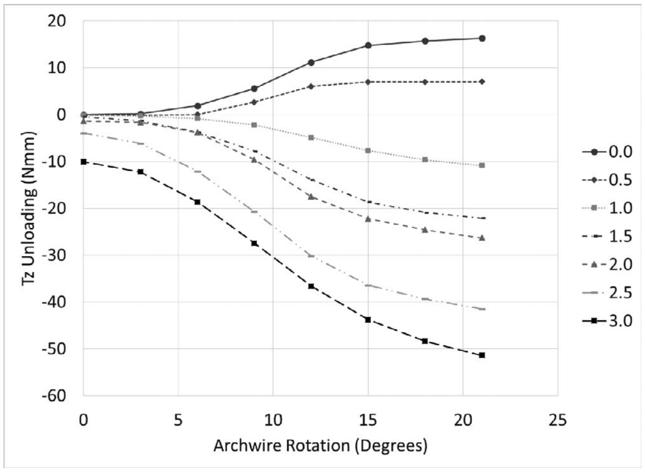

Figure 8. T_z during the unloading phase of torque simulation at prescribed second-order offset angles.

of significant difference between the 1.5° and 2.0° misalignments is unexpected given that the 0.5° vs 1.0° and 1.0° vs 1.5° comparisons showed significant differences. A likely explanation for this centers on the fact that the second-order critical angle of engagement, 1.6°, is straddled by these angles. Again, considering bracket-archwire slop and dimensional tolerances, it is not unrealistic to envision a scenario in which a misalignment of 1.5°, theoretically below the critical angle, actually generated contact with the mesial-distal bracket edges while a misalignment of 2.0° did not. In such scenarios, it could be expected that the resulting T_z behavior during archwire rotation would be very similar, as was found here.

In comparing Figures 7 and 8, namely, the curves at 2.5° and 3.0° of misalignment, plastic deformation is apparent based on the initial and final values of T_z. Upon rotating the bracket in the second-order direction, initial values of T_z were found to be approximately 10 Nmm and 19 Nmm for 2.5° and 3.0° misalignments, respectively. After the archwire rotation protocol, the final T_z magnitudes reduced to approximately 4 Nmm and 10 Nmm at 2.5° and 3.0° misalignments, respectively, a reduction of nearly one-half the original value. This would indicate that the bracket and/or archwire were subject to substantial amounts of plastic deformation during the experimental procedure. When inspecting other misalignment angles and the corresponding T_z values, this effect is not nearly as pronounced.

Clinically, it can be suggested from these results that if a slight second-order rotational misalignment were present during third-order torque procedures, the third-order results should not change. Conversely, second-order misalignments generated T_z values that could result in tooth movement. Misalignments of greater than 1° resulted in T_z values surpassing the 5-Nmm thresholds for archwire rotations as low as approximately 10°. Thus, for a minor misalignment present during third-order rotations, second-order rotations may also arise. Lastly, due to the large T_z arising from misalignments, asymmetrical bracket plastic deformation may result. This in turn would alter the shape of the slot and may have implications in subsequent treatment protocols.

As with any experimental study, there are limitations to the procedure that must be discussed. Primarily, the configuration of the OTS used in this study did not account for biological factors, namely, periodontal ligament (PDL) compliance; however, the influence of including PDL compliance in third-order torque simulations has been found to minimally affect results.[14] While the lack of biological factors prevents discussion of phenomena such as tissue remodeling, the geometric considerations (eg, the twist in a wire, bracket-archwire misalignment, etc), which are what govern the generated orthodontic loads, are still representative of the oral environment. In addition, only passively ligated brackets were tested in this study. It is possible that actively ligated brackets may behave differently and should be investigated in the future.

CONCLUSIONS

- Second-order misalignments of 2.5° and 3.0° were found to have a statistically significant effect on third-order torque, T_x, for archwire rotation up to 21°.
- The maximum average mean difference in T_x, 2.54 Nmm, is arguably clinically irrelevant in light of large biological tissue property variations and bracket and/or archwire dimensional tolerances.
- For each increment of 0.5° in second-order misalignment, a statistically significant difference was found for each pairwise comparison except for 0.0° vs 0.5° and 1.5° vs 2.0° pairs.
- Initial and final T_z values differ greatly for larger angles of second-order misalignment, namely, 2.5° and 3.0°, suggesting that brackets were subjected to substantial plastic deformation.

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