Original Article

The biomechanics of posterior maxillary arch expansion using fixed labial and lingual appliances

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ABSTRACT
Objective: To compare the biomechanics of straight labial, straight lingual, and mushroom lingual archwire systems when used in posterior arch expansion.
Materials and Methods: An electro-mechanical orthodontic simulator allowing for buccal–lingual and vertical displacements of individual teeth and three-dimensional force/moment measurements was instrumented with anatomically shaped teeth for the maxillary arch. In-Ovation L brackets were bonded to lingual surfaces, and Carriere SLX brackets were bonded to labial surfaces to ensure consistency of slot dimensions. Titanium molybdenum archwires were bent to an ideal arch form, and the teeth on the orthodontic simulator were set to a passive position. Posterior teeth from the canine to second molar were moved lingually to replicate a constricted arch. From the constricted position, the posterior teeth were simultaneously moved until the expansive force decreased below 0.2 N. Initial force/moment systems and the amount of predicted expansion were compared for posterior teeth at a significance level of $\alpha = 0.05$.
Results: Archwire type affected both the expected expansion and initial force/moment systems produced in the constricted position. In general, the lingual systems produced the most expansion. The archwire systems were not able to return the teeth to their ideal position, with the closest system reaching 41% of the intended expansion.
Conclusions: In general, lingual systems were able to produce greater expansion in the posterior regions when compared with labial systems. However, less than half of the intended arch expansion was achieved with all systems tested. (*Angle Orthod.* 2020;90:688–694.)

KEY WORDS: Orthodontic biomechanics; Arch expansion; Orthodontic simulator; Fixed appliances

INTRODUCTION

With the advent of new bonding techniques, archwire materials, advanced laboratory techniques, and improved digital treatment planning techniques,[1,2] fixed lingual appliances pose a potential esthetic alternative to fixed labial appliances. Despite their potential alternative, there is limited literature on the biome-

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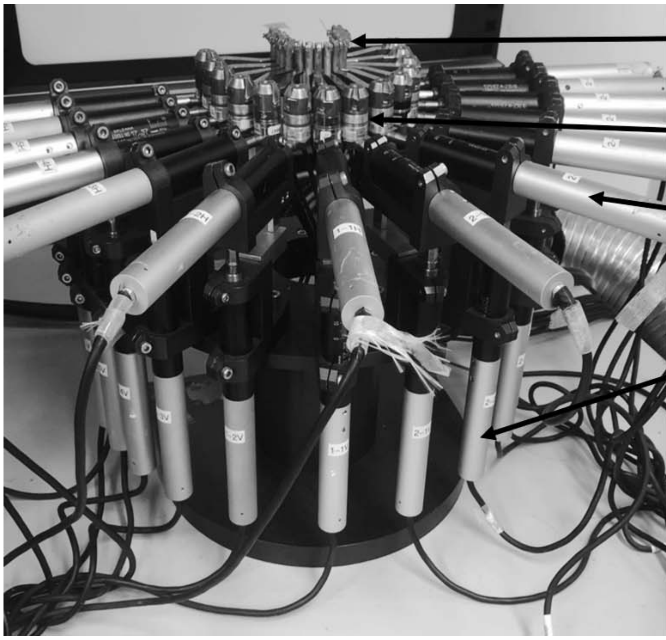

Figure 1. Overall schematic of the orthodontic simulator, an in vitro electromechanical device used to measure force and moment systems on each tooth.

chanical behavior[3,4] of fixed lingual appliances. As forces and moments generated by activated appliances are the driving factors for resulting tooth movement, understanding the biomechanics of lingual fixed appliances is critical for their clinical efficacy.

The biomechanics of fixed lingual mechanotherapy is different from that of fixed labial appliances as the point-of-force application with respect to the center of resistance (CR) of teeth varies between the two appliances and the interbracket distance is substantially smaller in lingual treatment. The mushroom lingual archwire, introduced by Fujita,[5] has a first-order bend between the canine and first premolar that increases the length of archwire between the canine and first premolar. The bend also alters how the archwire deforms when exposed to tooth movements that, in turn, affects the magnitude of applied forces and moments. The first-order bend further allows for a close adaptation of brackets to the teeth for the mushroom lingual archwire. The straight lingual archwire[6] requires a thicker composite base between the tooth and bracket that further decreases the interbracket distance for the lingual appliance and can potentially change the location of load application with respect to the CR.[7] Prior research has also demonstrated significant differences in the biomechanical systems of straight and mushroom lingual archwires.[7,8]

Dental arch expansion through an engaged archwire is one of the strategies used in orthodontics to resolve dental crowding. Grauer and Proffit[9] demonstrated that fully customized lingual orthodontic appliances were accurate in achieving the goals planned in the initial set-up with the exception of the full amount of planned expansion. Other authors have suggested that lingual appliances have restrictive transverse effect when compared with their labial counterpart in the premolar and molar region.[10,11] Although qualitative evidence surrounding archwire expansion exists, quantitative evidence regarding the amount of expected expansion and the force and moment systems produced remains elusive. Thus, the overall goal of this in vitro study was to elucidate the initial biomechanical systems produced by straight lingual, mushroom lingual, and fixed labial appliances and to simulate the expected amount of expansion for posterior teeth using an expected force threshold to produce tooth movement.

MATERIALS AND METHODS

An in vitro electro-mechanical orthodontic simulator (OSIM; Figure 1) was used to quantify the forces and moments generated around a simulated maxillary arch. A full detailed description of the OSIM and its components for reference was provided in previous studies.[7,12] Briefly, it has horizontal and vertical micrometers that allow for the control of simulated tooth movement in the buccal–lingual and vertical directions, respectively. The point of load application at simulated teeth is away from the point of load measurement using six-axis load cells (Nano17, ATI Industrial Automation, Apex, NC), which are rigidly fixed to the simulated teeth, as highlighted in Figure 1. A FARO arm coordinate measurement machine (FARO, Lake Mary, Fla) was used to determine the

Table 1. Sign Conventions for Positive Sense of Forces and Moments of Interest in Quadrants 1 and 2 of the Simulated Maxillary Arch[a]

Region	Fx	Fy	Mx
Quadrant 1	Mesial	Buccal	Moment causing buccal root tip
Quadrant 2	Distal	Buccal	Moment causing buccal root tip

[a] Fx indicates mesial–distal force; Fy, buccal–lingual force; Mx, third-order moment.

Table 2. Lingual Movement of Teeth to Simulate a Constricted Maxillary Arch

Tooth	Lingual Movement (mm)
Second molar	0.96
First molar	1.65
Second premolar	1.83
First premolar	1.70
Canine	0.69

Jacobian transformation matrices between the load cell and approximated CR of each tooth, as reported in previous work.[7] The OSIM has been used previously to investigate force and moment systems in simulated malocclusions for both fixed labial[12] and lingual appliances.[7] The sign conventions for forces and moments of interest in this study are provided in Table 1. Fy represents the amount of force directed in the buccal–lingual direction causing expansion, and Mx represents the expected third-order moment that would arise from the applied expansion force at a distance from the CR. As the OSIM can only move teeth in the buccal–lingual and vertical directions, Fx was also of interest to observe how much force in the mesial–distal direction arises compared with the expected expansion force direct in the buccal direction.

Simulated stainless steel teeth on the OSIM were positioned corresponding to a mushroom lingual arch form. In-Ovation L brackets with a 0.018″ × 0.025″ nominal slot dimension (Dentsply GAC, York, Pa) were bonded using Transbond XT (3M Unitek, Morovia, Calif) on the lingual surfaces of the simulated teeth. The teeth were moved so that all forces and moments acting on any tooth were less than 0.1 N and 5 Nmm, respectively. The resulting archform represented the ideal position for all groups tested. After the set-up for mushroom lingual archwire was completed, measurements using 0.0175″ × 0.0175″ custom bent mushroom lingual titanium molybdenum archwires (G&H Orthodontics, Franklin, Ind) were obtained. Following the mushroom lingual archwire tests, the brackets were rebonded to conform with a 0.0175″ × 0.0175″ straight lingual archwire also made from titanium molybdenum (G&H Orthodontics). A similar procedure was followed for straight labial archwire testing where Carriere SLX brackets (Henry Schein Orthodontics, Carlsbad, Calif), also with a 0.018″ × 0.025″ nominal slot size, and 0.0175″ × 0.0175″ labial titanium molybdenum archwires (G&H Orthodontics) were used.

For all three archwire groups, teeth from the canine to second molar were moved in the lingual direction to a narrow position simulating a constricted maxillary arch (Table 2). Constricted values were first set using a mushroom lingual archwire based on the mean measured expansion per tooth in a related clinical study by Mikulencak.[13] They were then adjusted to ensure any cases of buccal-directed force were mitigated to achieve an idealized initial position. In comparing the lingual displacements per tooth from the current study in Table 2 to those from Mikulencak,[13] the values used in this study were within one standard deviation of the data from the clinical study.

Upon moving teeth from the canine to the second molar to the initial constricted position, forces and moments of interest were recorded. From that position, any tooth that had buccal forces (Fy) larger than a threshold of 0.2 N were simultaneously moved in the buccal direction by 0.01 mm. This incremental operation occurred on a given tooth until the measured Fy force fell below the threshold. The procedure for a given archwire trial continued until all teeth from the canine to the second molar had Fy values below 0.2 N. The threshold of 0.2 N was conservatively based on the minimum force levels found in the orthodontic literature that resulted in clinically observed tooth movements.[14–16] The distance that the teeth were moved was recorded for each archwire. The percentage of expansion achieved by the appliance was defined as a ratio between the total buccal displacement produced at a particular tooth and the amount of initial lingual movement to the constricted position. Archwires ($n = 30$/group) were bent by a single experienced clinician (Dr Owen) using a template.

For each archwire tested (ie, per trial), the initial force and moment values and the amount of expansion for each tooth (eg, canine in the first and second quadrants) were averaged across the arch. Repeated measures of analysis of variance were used to assess the forces/moments and amount of expansion among the straight labial, mushroom lingual, and straight lingual archwires. Multiple comparisons were adjusted using Bonferroni corrections. Statistical significance was set at 0.05.

RESULTS

The expansion data for all teeth are presented in Tables 3 and 4. All three archwires produced maximum expansion on the first premolar where straight lingual expanded the first premolar by 0.70 mm and straight labial and mushroom lingual archwires by 0.42 mm. The second molar experienced no expansion with any

Table 3. Mean Expansion for the Three Archwire Groups Tested and Their Percent Expansion (n = 30 for Each Archwire)

Tooth	Group	Mean Expansion (mm) ± SD[a]	% Expansion
Second molar	Straight labial	−0.02 ± 0.034	–
	Straight lingual	0.00 ± 0.000	–
	Mushroom lingual	−0.02 ± 0.019	–
First molar	Straight labial	0.07 ± 0.096	4
	Straight lingual	0.36 ± 0.064	22
	Mushroom lingual	0.07 ± 0.116	4
Second premolar	Straight labial	0.18 ± 0.075	10
	Straight lingual	0.46 ± 0.129	25
	Mushroom lingual	0.18 ± 0.102	10
First Premolar	Straight labial	0.42 ± 0.070	25
	Straight lingual	0.70 ± 0.159	41
	Mushroom lingual	0.42 ± 0.119	25
Canine	Straight labial	0.14 ± 0.073	20
	Straight lingual	0.19 ± 0.090	28
	Mushroom lingual	0.15 ± 0.060	22

[a] SD indicates standard deviation.

of the three archwires. Straight lingual archwires created significantly ($P < .05$) more expansion on all teeth compared with the mushroom lingual and straight labial archwires. Specifically, the straight labial and mushroom lingual archwires produced comparable expansion (0.42 mm), but significantly less ($P < .001$) than the straight lingual archwire for the first premolar. For the second premolar and first molar, the straight lingual archwire produced significantly greater expansion ($P < .001$ and $P < .001$, respectively) compared with the straight labial and mushroom lingual archwires. The straight lingual archwire produced marginally ($P < .05$) more expansion compared with the straight labial and mushroom lingual archwires on the canine.

The initial Fy, Mx, and Fx values collected at the initial constricted position are provided in Tables 5 to 9. The maximum initial buccal force (straight lingual, 1.88 N; straight labial, 1.28 N; and mushroom lingual, 1.18 N) was measured on the first premolar for all groups with a significant difference ($P < .001$) between the straight lingual and the other two archwires. Straight lingual archwires exerted significantly larger initial buccal–lingual forces on all teeth except for the second premolar, where the mushroom lingual archwire measured the largest mean Fy (0.95 N). The straight labial archwires exerted the lowest initial force on all teeth except the first premolar where the mushroom lingual group was the lowest (1.18 N).

The maximum Mx was generated at the first premolar by the straight labial (12.81 Nmm), straight lingual (12.40 Nmm), and mushroom lingual (11.63 Nmm) archwires. The straight labial archwire produced significantly lower moment at the canine (0.35 Nmm) and first molar (0.02 Nmm) compared with the fixed lingual archwires. Moments varied among teeth for straight and mushroom lingual archwires. For the canine (–7.71 Nmm) and second premolar (–8.20

Table 4. Pairwise Comparisons of Expansion Among the Three Archwires With Bonferroni Corrections ($\alpha = 0.05$)[a]

Tooth	Group	Group	Mean Difference (mm)	SE	*P*	95% CI
Second molar	Straight labial	Straight lingual	−0.02	0.01	.01*	−0.03 to −0.00
		Mushroom lingual	≪0.01	0.01	1.00	−0.01 to 0.01
	Mushroom lingual	Straight lingual	−0.02	0.01	.01*	−0.03 to −0.00
First molar	Straight labial	Straight lingual	−0.29	0.02	.00**	−0.33 to −0.24
		Mushroom lingual	0.00	0.02	1.00	−0.05 to 0.05
	Mushroom lingual	Straight lingual	−0.29	0.02	.00**	−0.33 to −0.24
Second premolar	Straight labial	Straight lingual	−0.28	0.03	.00**	−0.33 to −0.23
		Mushroom lingual	0.00	0.03	1.00	−0.05 to 0.05
	Mushroom lingual	Straight lingual	−0.28	0.03	.00**	−0.33 to −0.23
First premolar	Straight labial	Straight lingual	−0.28	0.03	.00**	−0.34 to −0.23
		Mushroom lingual	0.00	0.03	1.00	−0.01 to 0.06
	Mushroom lingual	Straight lingual	−0.28	0.03	.00**	−0.34 to −0.23
Canine	Straight labial	Straight lingual	−0.05	0.02	.02*	−0.09 to −0.01
		Mushroom lingual	−0.01	0.02	.68	−0.05 to 0.03
	Mushroom lingual	Straight lingual	−0.04	0.02	.05	−0.08 to 4.9E-5

[a] CI indicates confidence interval; SE, standard error. * significant; ** highly significant.

Table 5. Mean Buccal–Lingual Forces, Fy, Acting on the Teeth of Interest (n = 30 for Each Archwire)

Tooth	Group	Mean (N) ± SD[a]
Second molar	Straight labial	−0.23 ± 0.09
	Straight lingual	−0.60 ± 0.05
	Mushroom lingual	−0.30 ± 0.26
First molar	Straight labial	0.08 ± 0.19
	Straight lingual	0.70 ± 0.10
	Mushroom lingual	−0.17 ± 0.41
Second premolar	Straight labial	0.03 ± 0.11
	Straight lingual	−0.29 ± 0.12
	Mushroom lingual	0.95 ± 0.45
First premolar	Straight labial	1.28 ± 0.28
	Straight lingual	1.88 ± 0.17
	Mushroom lingual	1.18 ± 1.14
Canine	Straight labial	0.04 ± 0.41
	Straight lingual	−0.67 ± 0.24
	Mushroom lingual	0.60 ± 1.09

[a] SD indicates standard deviation.

Table 7. Mean Third-Order Moment, Mx, Acting on the Teeth of Interest (n = 30 per Archwire)

Tooth	Group	Mean (Nmm) ± SD[a]
Second molar	Straight labial	−0.65 ± 1.87
	Straight lingual	3.65 ± 0.89
	Mushroom lingual	3.02 ± 1.97
First molar	Straight labial	0.02 ± 1.91
	Straight lingual	−6.07 ± 1.32
	Mushroom lingual	0.52 ± 2.80
Second premolar	Straight labial	−0.85 ± 1.25
	Straight lingual	−0.10 ± 1.15
	Mushroom lingual	−8.20 ± 3.73
First premolar	Straight labial	−12.81 ± 4.99
	Straight lingual	−12.40 ± 1.21
	Mushroom lingual	−11.63 ± 5.21
Canine	Straight labial	−0.35 ± 4.80
	Straight lingual	6.80 ± 2.77
	Mushroom lingual	−7.71 ± 6.59

[a] SD indicates standard deviation.

Nmm), the mushroom lingual archwire exerted significantly ($P < .001$) greater moment compared with the straight lingual archwire. Alternatively, the straight lingual archwire produced significantly more ($P < .001$) moment at the first molar (−6.07 Nmm) compared with the mushroom lingual archwire.

When considering Fx (mesial–distal forces), only the straight labial archwire produced a force on the second molar that surpassed the proposed threshold of 0.2 N necessary to cause tooth movement. Compared with buccal–lingual forces, Fy, the measured mesial–distal forces were substantially smaller in magnitude (Table 9).

DISCUSSION

Initial force levels and the total amount of expansion varied among the tested archwire groups. Maximum expansion, expansion buccal–lingual forces, and moments were observed at the first premolar for all three archwire groups. There was negligible expansion and initial expansion forces exerted by any of the three archwire groups on the second molar.

The fixed straight lingual archwire produced more mean expansion than the labial counterpart and mushroom lingual archwire for the same amount of activation for almost all the tested teeth. The interbracket distance between teeth (ie, length of archwire between two teeth) is less for the fixed lingual appliances compared with a fixed labial appliance. The reduced distance increases the stiffness of an archwire, and thus the force generated is more by the two lingual archwire systems compared with the labial archwire. However, the initial buccal forces generated at the first premolars by the mushroom lingual archwire was less compared with the other two archwires. This could be explained by the first-order bend between the canine and first premolar that incorporates more

Table 6. Pairwise Comparisons of Buccal–Lingual Forces, Fy, With Bonferroni Corrections ($\alpha = 0.05$)[a]

Tooth	Group	Group	Mean difference (N)	SE	P	95% CI
Second molar	Straight labial	Straight lingual	0.35	0.05	<.001**	0.28 to 0.46
		Mushroom lingual	0.07	0.05	.10	−0.2 to 0.16
	Mushroom lingual	Straight lingual	0.30	0.05	<.001**	0.21 to 0.39
First molar	Straight labial	Straight lingual	−0.62	0.07	<.001**	−0.75 to −0.48
		Mushroom lingual	0.25	0.07	.001**	0.11 to 0.38
	Mushroom lingual	Straight lingual	−0.86	0.07	<.001**	−0.99 to −0.73
Second premolar	Straight labial	Straight lingual	0.32	0.08	<.001**	0.17 to 0.47
		Mushroom lingual	−0.92	0.08	<.001**	−1.07 to −0.76
	Mushroom lingual	Straight lingual	1.24	0.08	<.001**	1.09 to 1.39
First premolar	Straight labial	Straight lingual	−0.61	0.18	.001**	−0.96 to −0.26
		Mushroom lingual	0.10	0.18	.58	−0.25 to 0.45
	Mushroom lingual	Straight lingual	−0.71	0.18	<.001**	−1.06 to −0.35
Canine	Straight labial	Straight lingual	0.71	0.18	<.001**	0.37 to 1.06
		Mushroom lingual	−0.56	0.18	.002**	−0.91 to −0.21
	Mushroom lingual	Straight lingual	1.27	0.18	<.001**	0.92 to 1.62

[a] CI indicates confidence interval; SE, standard error; **, highly significant.

Table 8. Pairwise Comparisons of Third-Order Moments, Mx, of the Three Archwires With Bonferroni Corrections ($\alpha = 0.05$)[a]

Tooth	Group	Group	Mean Difference (Nmm)	SE	*P*	95% CI
Second molar	Straight labial	Straight lingual	−4.30	0.43	<.001**	−5.15 to −3.45
		Mushroom lingual	−3.68	0.43	<.001**	−4.52 to −2.83
	Mushroom lingual	Straight lingual	−0.62	0.43	.15	−1.47 to 0.23
First molar	Straight labial	Straight lingual	6.10	0.54	<.001**	5.02 to 7.18
		Mushroom lingual	−0.50	0.54	.36	−1.57 to 0.58
	Mushroom lingual	Straight lingual	6.59	0.54	<.001**	5.51 to 7.67
Second premolar	Straight labial	Straight lingual	−0.75	0.61	.22	−1.96 to 0.46
		Mushroom lingual	7.34	0.61	<.001**	6.13 to 8.56
	Mushroom lingual	Straight lingual	−8.09	0.61	<.001**	−9.31 to −6.88
First premolar	Straight labial	Straight lingual	−0.41	1.09	.71	−2.58 to 1.75
		Mushroom lingual	−1.18	1.09	.28	−3.34 to 0.99
	Mushroom lingual	Straight lingual	0.76	1.09	.49	−1.40 to 2.93
Canine	Straight labial	Straight lingual	−7.15	1.28	<.001**	−9.70 to −4.60
		Mushroom lingual	7.36	1.28	<.001**	4.80 to 9.91
	Mushroom lingual	Straight lingual	−14.51	1.28	<.001**	−17.06 to −11.95

[a] CI indicates confidence interval; SE, standard error; **, highly significant.

archwire length and the changed shape of the archwire that could alter the resulting mechanics. The initial buccal force levels were significantly more with straight lingual archwires compared with the mushroom lingual archwires possibly because of the short interbracket span[17] of straight lingual archwires caused by the increased thickness of the composite base for the bracket compared with closely adapted mushroom lingual brackets.

All three archwires generated clinically significant (>5 Nmm)[7] moments on the first premolars even though an archwire cross-section of 0.0175 × 0.0175 titanium molybdenum archwire (TMA) was used that is suggested to be of sufficient thickness to create a couple (in the 0.018″ × 0.025″ bracket system) to counter the moment created by the application of force away from the CR of the tooth.[18] Moments generated by the three archwires concurred with the applied forces except for the canine where mushroom lingual archwires generated more moment that could tip the root buccally compared with the straight lingual archwires that generated an opposing moment that could potentially tip the root lingually. This again probably resulted because of the shape of the mushroom lingual archwire between the canine and first premolar that changed the biomechanics compared with a straight archform. Fixed labial archwires had less moment generated compared with fixed lingual archwires. This is in accordance with the difference in the force applied by the fixed labial and fixed lingual appliances. This reflects that there will be less of a change in third-order rotation with fixed labial appliances compared with fixed lingual appliances.

Overall, all three archwires produced less than 42% of the intended expansion with maximum expansion at the premolar region. These results were consistent with the clinical results of the study by Grauer and Proffit[9] that suggested that a fully customized lingual appliance did not achieve the full planned expansion. Therefore, clinically, this study suggests minimum activation to be twice the intended expansion for both labial and lingual fixed archwires in orthodontic patients. Straight lingual archwires produced more expansion than the mushroom lingual and straight labial archwires on the tested teeth for a simulated constricted arch. From a clinical standpoint, should archwire expansion be a likely component of treatment, these results make a good argument for using straight lingual archwires for constricted arch cases. Interestingly, the second molar experienced a restrictive transverse effect with all three archwires for 0.96 mm of activation. Thus, in a clinical scenario, archwire expansion may not be adequate for expansion at the second molar for 0.96 mm of activation, and alternate methods such as overlay wires could be applied.

Table 9. Mean Mesial–Distal Forces (Fx) Acting on Teeth of Interest at the Initial Crowded Position for Labial Straight, Lingual Straight, and Lingual Mushroom Archwires

Archwire Group	Second Molar, Fx (N)	First Molar, Fx (N)	Second Premolar, Fx (N)	First Premolar, Fx (N)	Canine, Fx (N)
Mushroom lingual	−0.15	0.15	−0.14	0.18	0.13
Straight lingual	0.03	0.04	−0.01	0.14	−0.09
Straight labial	−0.25	0.05	−0.09	0.15	0.07

As with any in vitro study, there are inherent limitations that should be considered regarding the presented findings. Only one type of bracket and archwire system was used along with a representative approximation of the CR. Variations of these variables could produce differing magnitudes of results, but the comparisons between treatments are expected to remain consistent. Forces in the mesial–distal direction (Fx) and their potential effect on subsequent simulated tooth movement were not considered in this study. Forces on all teeth in the mesial–distal direction, except one instance, were below the clinically significant levels of 0.2 N (Table 6). Thus, it is expected that Fx would have a minimal contribution in the direction of movement away from the buccal–lingual direction. A relatively larger standard deviation of results was noted for the mushroom archwire system compared with the straight systems. This discrepancy was likely attributable to the introduction of the first-order bend and slight variations surrounding the bend and engagement with the brackets. Finally, teeth were only translated to simulate movement. It is expected that some amount of tooth rotation would occur based on the measured third-order moments. Although this was not accounted for, the change in bracket position is still expected to be similar to what was predicted in this study but composed of rotation and translation as opposed to solely translation.

CONCLUSIONS

- The fixed straight lingual archwire generally produced more simulated mean expansion than the straight labial and mushroom lingual archwires for the same initial crowded position.
- All three archwires tested produced less than 42% of the intended expansion to a neutral position.
- Initial force levels and the total amount of expansion varied among the three tested archwire systems.

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