In vitro measurement of the initial forces and moments generated for a curve of Spee malocclusion with labial and lingual archwire forms

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ABSTRACT

Objectives: To compare the biomechanics of labial and lingual fixed orthodontic treatment options for a simulated curve of Spee malocclusion.

Materials and Methods: An in vitro electromechanical orthodontic simulator was used to measure the three−dimensional forces and moments on each tooth of a mandibular arch. Labial and lingual brackets, both with 0.018−inch slot sizes, were bonded to mechanical teeth. Three archwire forms were considered: labial straight, lingual straight, and lingual mushroom. The simulator was set in a passive levelled position with 0.016−inch × 0.022−inch stainless steel archwires, then teeth were moved to a curve of Spee maloclussion with the first premolar intruded 1.5 mm and the canine and second premolar intruded 0.75 mm. Two−way mixed multivariate analysis of variance ($\alpha = 0.05$) was used to compare forces and moments generated among the three archwires.

Results: Statistical differences were found in 55 of 63 comparisons of forces and moments between archwire types for each tooth around the arch. The lowest force magnitudes were measured for labial straight archwires at each tooth position. The lateral incisor experienced the largest gingival forces with all archwire forms. The first premolar and first molar experienced labial−lingual crown tipping moments in opposite directions between labial and the two lingual archwire forms.

Conclusions: Biomechanical differences between labial, lingual straight, and lingual mushroom treatment modalities for the correction of curve of Spee misalignments were elucidated. Labial straight archwire exerted the lowest force magnitudes overall. For both lingual archwire forms, the labial−lingual inclination of the first premolar could be highly variable during levelling. (*Angle Orthod*. 2025;95:35–42.)

KEY WORDS: Curve of Spee; Orthodontic biomechanics; Orthodontic simulator; Lingual orthodontics; Labial orthodontics; Fixed appliance

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INTRODUCTION

Orthodontic patients commonly base successful treatment on how their teeth fit functionally and esthetically, but research has also shown visual impact of the appliance to be a primary factor.[1] Additionally, a patient's decision for orthodontics is correlated with the psychosocial perception related to the influence of appearance during treatment.[2] As a result, an increased demand for esthetic orthodontic treatment has been seen globally.[3] Orthodontic lingual brackets provide an esthetic advantage over labial systems through their placement on the lingual surface of teeth, and have similar overall patient satisfaction and treatment outcomes.[4] Lingual treatment also has lower risk of caries[5] and decalcification,[6] but increased oral discomfort, speaking, and chewing dysfunction.[7]

Although lingual and labial systems may both prove suitable depending on a range of factors (eg, malocclusion severity), they have different biomechanical considerations with distinct bracket locations[8] and archwire forms.[9] Lingual brackets are generally closer to the tooth's center of resistance (C_{res}),[10] and as such, the same force creates a different moment around C_{res}. Both appliances can use straight (parabolic) archwire forms, with the lingual version narrower and smaller in size.[9] Lingual brackets can also use a mushroom archwire that includes a bend to accommodate the lingual anatomical step between the canine and first premolar.[9] Between the anterior teeth, lingual brackets are closer together, which increases forces due to increased archwire stiffness.[10–12]

A fundamental orthodontic goal is to level the curve of Spee,[13] the sagittal arc determined by the mandibular dental cusps and incisal edges.[14] It has a functional role in mastication,[15] establishing balanced occlusion,[14] and temporomandibular joint disorders.[16] The curve of Spee is the biggest contributor to deep overbite,[17] and a flat occlusal plane helps achieve ideal occlusal interdigitation.[13] The specific dental movements for orthodontic correction are more dependent on clinical management[17,18] than the initial curve of Spee depth.[17,18]

Orthodontic literature has recognized the need for further biomechanical investigations between lingual and labial appliances[3] as it may have clinical implications.[19] With respect to leveling, uprighting of a second molar was associated with more relapse, and segmental and continuous archwires produced stable results.[20] No statistical differences were found between labial straight archwires of different materials (stainless steel, multistranded steel or nickel titanium),[21] size (0.016−inch vs 0.016−inch by 0.022−inch),[22] or amount of reverse curve.[23] Based on mathematical modeling, archwire form is suggested to affect curve of Spee leveling;[24] two versions of labial straight archwire had different arch−length implications,[22] and lingual mushroom archwire with reverse−curvature intruded lower incisors.[25] However, direct comparisons between labial and lingual systems to level the curve of Spee are lacking.

The objective of the present study was to understand differences in initial forces and moments generated by lingual and labial appliances in a simulated curve of Spee malocclusion. Results were compared to elucidate biomechanical differences among the three treatment types to better understand potential outcomes, desirable and undesirable. In turn, decisions surrounding treatment modality, and potential corrective measures, can be better informed based on an individual patient case and known biomechanics for curve of Spee correction.

MATERIALS AND METHODS

The Orthodontic SIMulator (OSIM) is an in vitro apparatus used to measure three−dimensional forces and moments acting on individual teeth along a single dental arch.[26] Forces and moments are measured by six−axis load cells (Nano17, ATI Industrial, Apex, NC, USA) rigidly attached to each tooth. Measurements are transformed relative to the tooth's theoretical C_{res} using a FARO Arm (FARO Technologies, United States) coordinate measurement machine to generate Jacobian transformation matrices, as described previously by Owen et al.[27] Labial and lingual self−ligating 0.018−inch brackets (SLX, Carriere, Carlsbad, CA, USA and In−Ovation L, Dentsply GAC, York, PA, USA, respectively) were bonded to stainless−steel teeth using metal primer (Reliance Ortho Products Inc.), bonding agent (OrthoSolo, Ormco, Orange, CA, USA), and composite resin (3M Unitek Transbond XT).

The OSIM arch consisted of all teeth, excluding third molars. Brackets were bonded to the approximate middle of the crown using a bonding jig to passively fit each archwire. An archwire form template for each group was first established to which the jig and experimental archwires were fabricated. Three mandibular archwire forms, comprised of 0.016−inch x 0.022−inch stainless−steel (G&H Orthodontics, Franklin, IN) were used: labial straight, lingual straight, and lingual mushroom (Figure 1). Once engaged, a zeroing procedure was performed to ensure a passive fit of the archwire in the brackets before each trial. The horizontal and vertical micrometers were adjusted for each load cell to measure less than 0.1N of force in all directions. The curve of Spee maximum position was established by moving the second premolar and canine 0.75 mm and the first premolar 1.5 mm gingival to the occlusal plane. Although there can be various curve of Spee positions, this setup was chosen to establish a symmetric and parabolic curve of Spee.

The forces and moments of interest were F_z in the occlusal−gingival direction and F_y and M_x in the labial−lingual direction, as these are the primary tooth movements occurring during curve of Spee correction (Figure 2). The y− and z−axes were in the same direction for each tooth; however, the local tooth coordinate system orients the x−axis differently as it crosses the dental arch midline to maintain a right−handed coordinate system: positive indicates a distal direction on one side, and a mesial direction on the other. The adjustments allowed for discussion of forces and moments in terms of clinical tooth movement directions. The force and moment values for the same

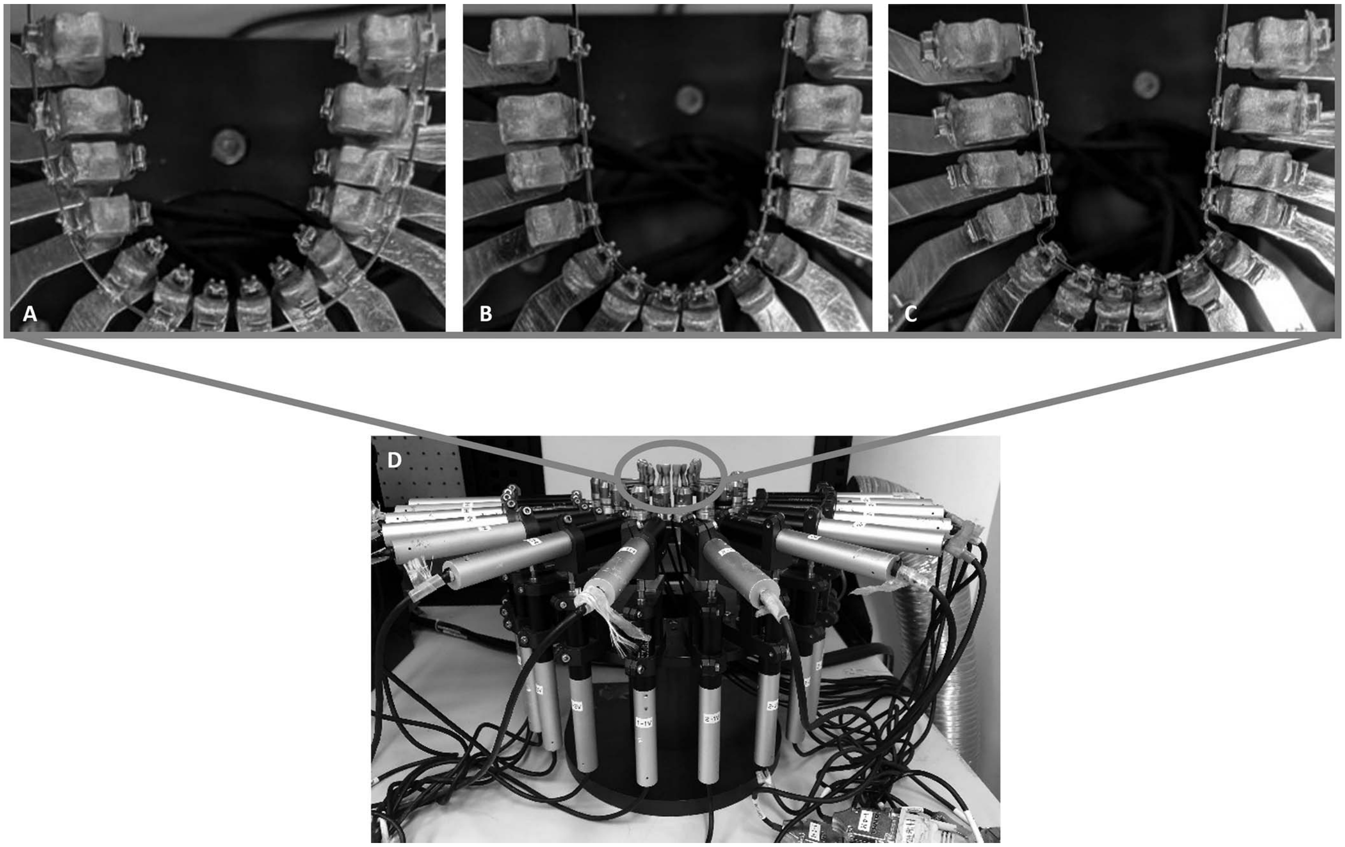

Figure 1. Experimental treatment groups. (A) Labial straight archwire. (B) Lingual straight archwire. (C) Lingual mushroom archwire. (D) The full OSIM setup showing the location of the simulated arch on the overall apparatus. OSIM indicates Orthodontic SIMulator.

tooth on the left and right side of OSIM were averaged for each archwire.

A systematic review proposed 0.18N as the lowest force magnitude to produce tooth movement,[28] and Andreasan et al. concluded only forces exceeding 15gm (0.15N) transmitted to the periodontal ligament produced tooth movement.[29] Moments of 3Nmm have been proposed to produce appreciable tooth movement.[30] Although the literature has not yet established a consensus on the minimum forces and moments required for tooth movement, forces above 0.2N and moments above 3Nmm were considered clinically significant based on available supporting data.

To detect the minimum force 0.2N and setting the statistical power, $1 - \beta = 0.9$, and type I error rate, $\alpha = 0.05$, the sample size for each experimental group (labial straight, lingual straight, and lingual mushroom), was estimated as $n = 61$ trials. The standard deviations necessary for the sample size calculation were estimated from a pilot study. Two−way mixed multivariate analysis of variance (MANOVA) was conducted with IBM SPSS to determine differences in the forces and moments using a significance level of $\alpha = 0.05$. Statistical significance was unaffected with and without multivariate outliers, and, therefore, the reported analysis includes all data values. Greenhouse−Geisser correction was used for multivariate hypothesis statistical analysis, and Bonferonni correction was used for post−hoc pairwise comparisons.

RESULTS

The means and standard deviations for each tooth are shown in Figure 3. All values were above the discussed minimal threshold to be clinically significant, except for F_z on the central incisor for all archwire forms and M_x on the second molar and first premolar for the labial straight archwire. The two−way mixed MANOVA with Pillai's Trace *F*−test statistic indicated convincing evidence that Fz, Fy and Mx are dependent on a statistically significant interaction effect (*P* value $< .05$) with two factors: archwire form (three levels) and mandibular tooth position (seven levels). The effects of mandibular tooth position and archwire form were also statistically significant (*P* value $< .05$). The effects based on tooth position or archwire form alone could not be quantified because of the statistically significant interaction. However, trends could be observed for tooth position or

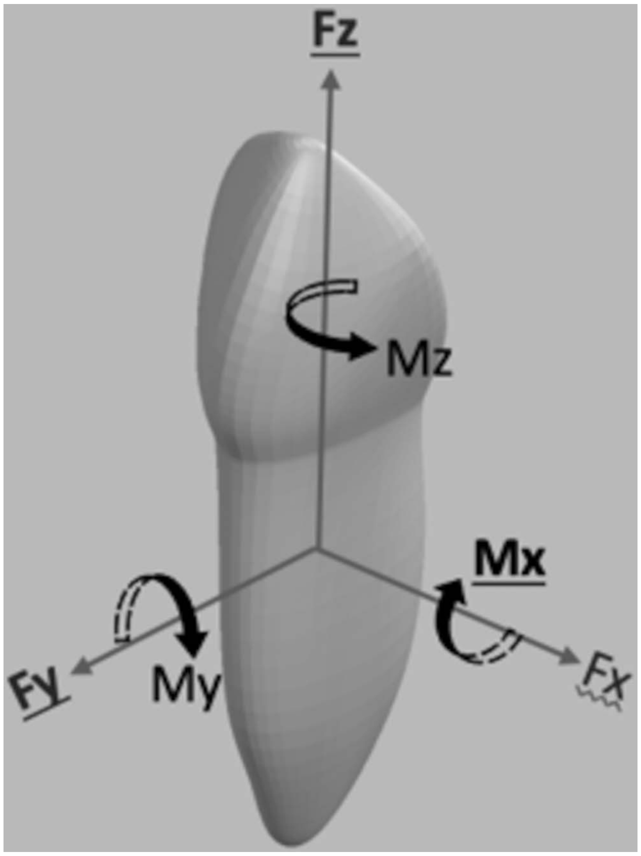

Figure 2. The force and moment coordinate system (main interests of this study are bolded underlined).

archwire form based on measurements, corroborated by pairwise comparisons with Bonferonni adjustment listed in Table 1.

The three archwire groups exerted similar F_z and F_y directions at different magnitudes on each tooth position. For F_z, the canine, first premolar, and second premolar experienced occlusal vectors, and the lateral incisor, first molar, and second molar experienced gingival vectors. For F_y, all archwire forms exerted labial forces on the lateral incisor and first molar, and lingual vectors on the central incisor, canine, first premolar, and second molar. The order of force magnitude between tooth positions was similar across groups, with the largest F_z and F_y forces on the lateral incisor. The labial straight archwire exerted forces with the lowest magnitude for all tooth positions.

The two lingual archwires exerted lingual crown tipping on the central incisor, canine, first molar, and second molar and labial crown tipping on the lateral incisor, first premolar, and second premolar. The labial straight archwire exerted opposite M_x directions on the first premolar and first molar. The labial straight archwire exerted the largest absolute M_x magnitudes on the lateral incisor, first premolar, and first molar. On the first premolar, the labial straight archwire exerted the greatest overall lingual crown tipping, and both lingual archwires forms exerted labial crown tipping. The standard deviations of the two lingual archwire forms on the first premolar were larger than any other measured outcome variable.

DISCUSSION

This in vitro study found statistically significant differences in the measured forces and moments between labial and lingual archwire forms on mandibular teeth in a curve of Spee malocclusion. The primary forces and moments of interest were the occlusal–gingival forces, and labial–lingual forces and moments. The majority of values recorded were above the chosen clinically significant threshold. The three archwire forms commonly used with labial and lingual orthodontics exerted a similar pattern of initial occlusal–gingival and labial–lingual forces on the mandibular teeth with a curve of Spee. The occlusal–gingival force vectors were appropriate to level the curve of Spee; teeth positioned below the occlusal plane received occlusal forces at magnitudes relative to their displacement.

With respect to labial–lingual moments, differences between archwire forms may have clinical considerations. The labial straight archwire exerted crown tipping moments that would exacerbate the labial–lingual forces on the crown portion of the first premolar and first molar, whereas lingual archwire forms exerted labial–lingual moments that would tip crowns opposite to the labial–lingual forces (Figure 4). As a result, the crowns of posterior teeth may have increased transverse effects with labial archwires, seen clinically as narrowing between the first premolars and widening between the first molars. Depending on the specific case, mitigation of such effects may be achieved through integration of other corrective measures (eg, Class II elastics).

Both lingual archwire forms tested may produce unpredictable torque control on the first premolars based on determined standard deviations. Previous research similarly suggested decreased torque control during vertical movements with lingual appliances.[10] This may signify better predictability of the labial–lingual inclination of the first premolar with the labial straight archwire and decreased control with lingual archwires.

Research has demonstrated root resorption to be positively correlated with force magnitudes.[31,32] Among the archwire forms, the force magnitudes were the lowest with labial straight archwires, likely due to the increased interbracket distances.[11] Similar results were found with another in vitro study aligning a displaced central incisor.[12] Special attention to the lateral incisors

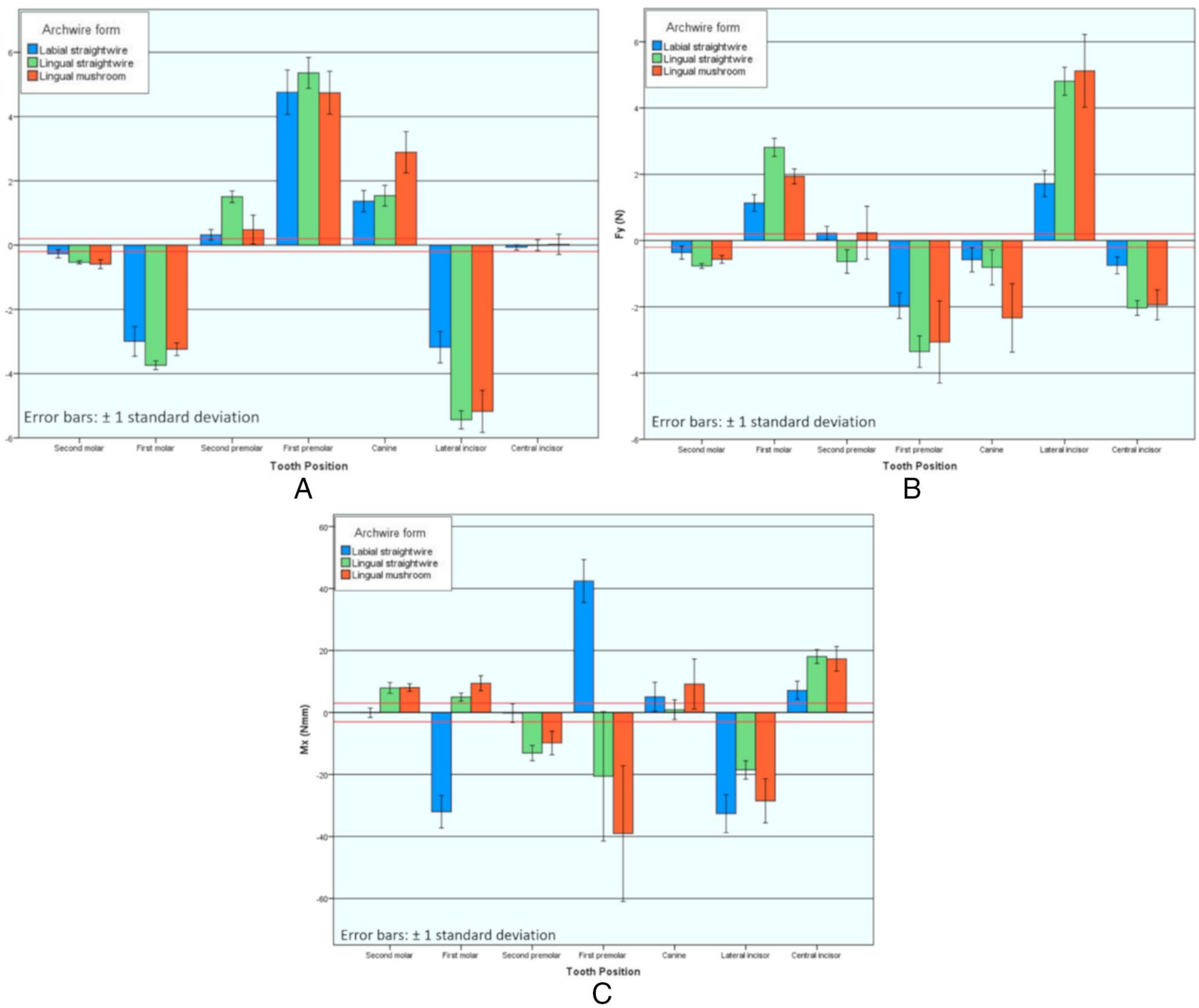

Figure 3. Mean values and standard deviations for: (A) F_z, where positive values and negative values indicate labial and lingual directions, respectively; (B) F_y, where positive values and negative values indicate labial and lingual directions respectively; and (C) M_x, where positive values and negative values indicate lingual and labial crown tipping, respectively. The red horizontal line on each plot indicates clinically significant force and moment levels at magnitudes of 0.2 N and 3N mm, respectively.

with any archwire form during leveling may be required since significant labial and gingival forces were recorded in this study. The gingival forces and labial−lingual moments acting on the lateral incisor may represent intrusion and lingual root torque, respectively, tooth movements most commonly associated with root resorption.[33] In addition, lateral incisors are already at high risk for root resorption with small conical roots.[31]

A recent systematic review concluded forces above 100gm (100 cN) increase the risks of root resorption,[32] and Proffit et al. proposed 120 gm (120 cN) forces to be the upper bound of optimal force levels.[34] Although many of the forces recorded were above these suggested levels, it is important to highlight that periodontal ligament (PDL) compliance was not replicated here and would likely reduce measured magnitudes. Given these considerations, labial archwires may be indicated for cases in which root resorption could be more debilitating (eg, poor periodontal support[31]) or higher−risk treatment protocols (eg, longer treatment duration or space closure). Lingual archwires may warrant treatment considerations during the leveling phase to prevent adverse side effects, such as using smaller dimensional or more flexible archwires.

Limitations of this study primarily surround its in vitro nature. The methodology did not replicate biological considerations such as saliva, PDL, pressure from soft tissues, masticatory forces, and interproximal

Table 1. Pairwise Comparisons Between Archwire Forms on Each Tooth for F_z, F_y, and M_x

Outcome	Tooth Position	Archwire Form A	Archwire Form B	Mean △(A−B) [95% CI]	*P* Value*
F_z (N)	Second molar	Labial SW	Lingual SW	0.27 [0.23, 0.31]	<**.001**
		Labial SW	Lingual MW	0.32 [0.28, 0.36]	<**.001**
		Lingual SW	Lingual MW	0.06 [0.02, 0.10]	**.007**
	First molar	Labial SW	Lingual SW	0.74 [0.64, 0.85]	<**.001**
		Labial SW	Lingual MW	0.24 [0.14, 0.35]	<**.001**
		Lingual SW	Lingual MW	−0.50 [−0.61, −0.39]	<**.001**
	Second premolar	Labial SW	Lingual SW	−1.19 [−1.29, −1.08]	<**.001**
		Labial SW	Lingual MW	−0.16 [−0.27, −0.06]	**.003**
		Lingual SW	Lingual MW	1.03 [0.92, 1.13]	<**.001**
	First premolar	Labial SW	Lingual SW	−0.60 [−0.82, −0.38]	<**.001**
		Labial SW	Lingual MW	0.02 [−0.21, 0.24]	.887
		Lingual SW	Lingual MW	0.62 [0.40, 0.84]	<**.001**
	Canine	Labial SW	Lingual SW	−0.17 [−0.34, −0.009]	**.039**
		Labial SW	Lingual MW	−1.52 [−1.68, −1.36]	<**.001**
		Lingual SW	Lingual MW	−1.35 [−1.51, −1.19]	<**.001**
	Lateral incisor	Labial SW	Lingual SW	2.26 [2.08, 2.44]	<**.001**
		Labial SW	Lingual MW	2.00 [1.82, 2.18]	<**.001**
		Lingual SW	Lingual MW	−0.26 [−0.44, −0.08]	**.004**
	Central incisor	Labial SW	Lingual SW	−0.07 [−0.14, 0.009]	.086
		Labial SW	Lingual MW	−0.09 [−0.17, −0.02]	**.015**
		Lingual SW	Lingual MW	−0.03 [−0.10, 0.05]	.459
F_y (N)	Second molar	Labial SW	Lingual SW	0.40 [0.35, 0.45]	<**.001**
		Labial SW	Lingual MW	0.21 [0.16, 0.26]	<**.001**
		Lingual SW	Lingual MW	−0.20 [−0.25, −0.15]	<**.001**
	First molar	Labial SW	Lingual SW	−1.68 [−1.77, −1.59]	<**.001**
		Labial SW	Lingual MW	−0.80 [−0.89, −0.71]	<**.001**
		Lingual SW	Lingual MW	0.87 [0.78, 0.96]	<**.001**
	Second premolar	Labial SW	Lingual SW	0.86 [0.67, 1.04]	<**.001**
		Labial SW	Lingual MW	−0.01 [−0.20, 0.17]	.884
		Lingual SW	Lingual MW	−0.87 [−1.06, −0.69]	<**.001**
	First premolar	Labial SW	Lingual SW	1.39 [1.10, 1.67]	<**.001**
		Labial SW	Lingual MW	1.10 [0.81, 1.38]	<**.001**
		Lingual SW	Lingual MW	−0.29 [−0.57, −0.004]	**.047**
	Canine	Labial SW	Lingual SW	0.23 [−0.02, 0.48]	.073
		Labial SW	Lingual MW	1.75 [1.50, 2.01]	<**.001**
		Lingual SW	Lingual MW	1.52 [1.27, 1.78]	<**.001**
	Lateral incisor	Labial SW	Lingual SW	−3.09 [−3.35, −2.83]	<**.001**
		Labial SW	Lingual MW	−3.40 [−3.66, −3.15]	<**.001**
		Lingual SW	Lingual MW	−0.31 [−0.57, −0.06]	**.017**
	Central incisor	Labial SW	Lingual SW	1.28 [1.17, 1.40]	<**.001**
		Labial SW	Lingual MW	1.19 [1.08, 1.31]	<**.001**
		Lingual SW	Lingual MW	−0.09 [−0.21, 0.03]	.122
M_x (Nmm)	Second molar	Labial SW	Lingual SW	−8.01 [−8.55, −7.47]	<**.001**
		Labial SW	Lingual MW	−8.14 [−8.67, −7.60]	<**.001**
		Lingual SW	Lingual MW	−0.13 [−0.67, 0.41]	.637
	First molar	Labial SW	Lingual SW	−37.02 [−38.24, −35.80]	<**.001**
		Labial SW	Lingual MW	−41.48 [−42.70, −40.26]	<**.001**
		Lingual SW	Lingual MW	−4.47 [−5.69, −3.25]	<**.001**
	Second premolar	Labial SW	Lingual SW	12.88 [11.75, 14.00]	<**.001**
		Labial SW	Lingual MW	9.62 [8.49, 10.74]	<**.001**
		Lingual SW	Lingual MW	−3.26 [−4.39, −2.14]	<**.001**
	First premolar	Labial SW	Lingual SW	63.02 [56.62, 69.42]	<**.001**
		Labial SW	Lingual MW	81.52 [75.12, 87.92]	<**.001**
		Lingual SW	Lingual MW	18.50 [12.10, 24.90]	<**.001**
	Canine	Labial SW	Lingual SW	4.17 [2.13, 6.20]	<**.001**
		Labial SW	Lingual MW	−4.12 [−6.16, −2.09]	<**.001**
		Lingual SW	Lingual MW	−8.29 [−10.33, −6.25]	<**.001**
	Lateral incisor	Labial SW	Lingual SW	−14.10 [−16.13, −12.07]	<**.001**
		Labial SW	Lingual MW	−4.13 [−6.16, −2.10]	<**.001**
		Lingual SW	Lingual MW	9.98 [7.95, 12.01]	<**.001**
	Central incisor	Labial SW	Lingual SW	−10.89 [−12.01, −9.77]	<**.001**
		Labial SW	Lingual MW	−10.17 [−11.28, −9.05]	<**.001**
		Lingual SW	Lingual MW	0.72 [−0.39, 1.84]	.20

* Bolded values indicate statistically significant values.

** The three experimental groups are labial straight (labial SW), lingual straight (lingual SW), and lingual mushroom (lingual MW).

contacts. Future studies comparing different archwire materials and sizes to further investigate curve of Spee malocclusion treatments are recommended to expand on clinical implications. Finally, there would be value in assessing different curve of Spee positions and severities as well since the position in this study was based on a 1.5 mm severity that was sagitally symmetric.

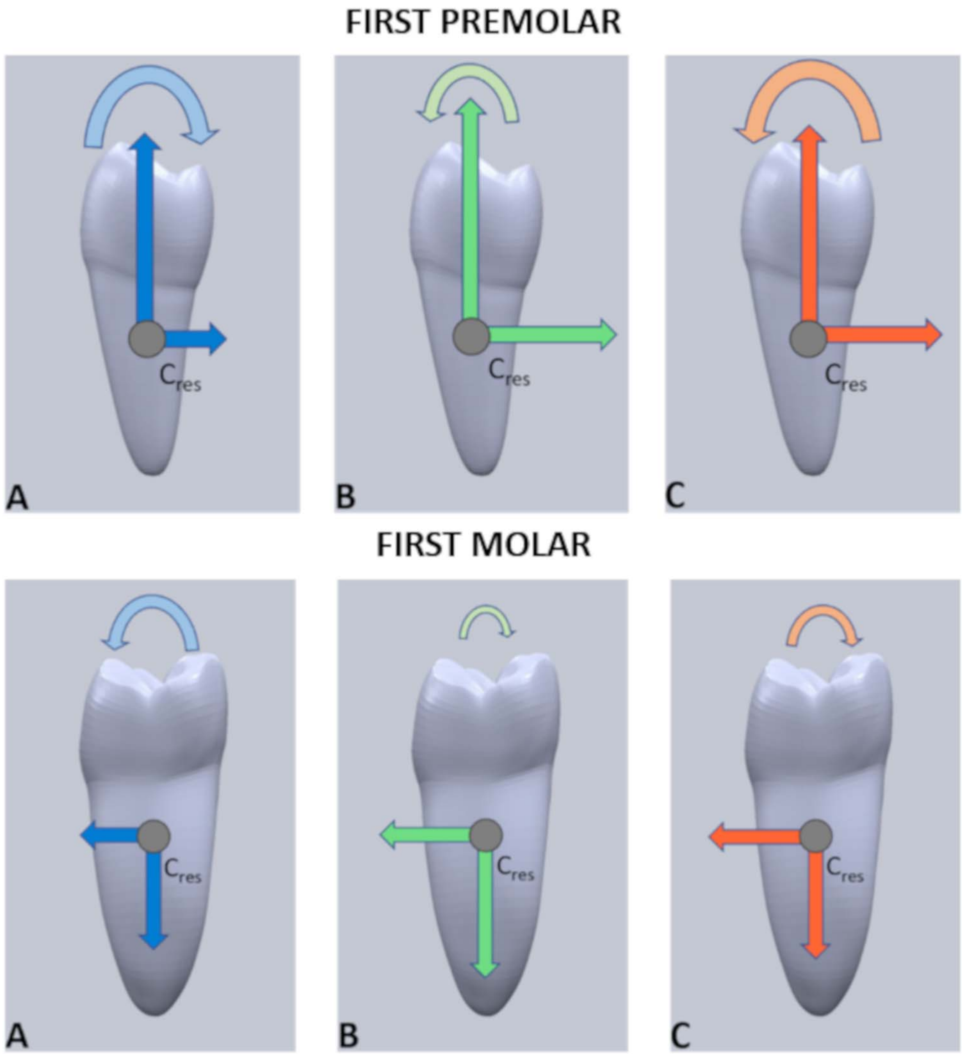

Figure 4. Sagittal view of the direction of forces and moments acting on the (top) first premolar and (bottom) first molar C_{res} for: (A) labial straight; (B) lingual straight; and (C) lingual mushroom archwire forms.

CONCLUSIONS

- Regardless of archwire form, the lateral incisor received large gingival forces and lingual root torque, which has increased concerns of root resorption.
- Labial straight archwire exerted the lowest force magnitudes and may have increased transverse effects on the crowns of posterior teeth.
- With both lingual archwire forms, the labial−lingual inclination of the first premolar could be highly variable during leveling. Regardless, tipping tended toward the buccal direction with lingual archwires and buccal direction with labial.

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