Original Article

Three-dimensional nonlinear prediction of tooth movement from the force system and root morphology

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ABSTRACT

Objectives: To determine the different impact of moment-to-force ratio (M:F) variation for each tooth and spatial plane and to develop a mathematical model to predict the orthodontic movement for every tooth.

Materials and Methods: Two full sets of teeth were obtained combining cone-beam computed tomography (CBCT) and optical scans for two patients. Subsequently, a finite element analysis was performed for 510 different force systems for each tooth to evaluate the centers of rotation.

Results: The center of C_{ROT} locations were analyzed, showing that the M:F effect was related to the spatial plane on which the moment was applied, to the force direction, and to the tooth morphology. The tooth dimensions on each plane were mathematically used to derive their influence on the tooth movement.

Conclusion: This study established the basis for an orthodontist to determine how the teeth move and their axes of resistance, depending on their morphology alone. The movement is controlled by a parameter (k), which depends on tooth dimensions and force system features. The k for a tooth can be calculated using a CBCT and a specific set of covariates. (*Angle Orthod.* 2020;90:811–822.)

KEY WORDS: Tooth movement; Biomechanics; Finite element analysis; Orthodontics

INTRODUCTION

The load system delivered by an orthodontic appliance to a specific tooth is the most important determinant factor in the quality of the resulting orthodontic movement. The resulting tooth movement in three dimensions (3D) will depend on specific 3D moment-to-force ratio (M:F) combinations. The current method to describe the type of tooth movement consists of measuring the distance from the tooth's projected axis of rotation (center of rotation; C_{ROT}) to the virtual intersection of the axes of resistance (center of resistance; C_{RES}). Some recent studies[1–4] and many previous studies[5–9] investigated the role of M:F associated with different tooth movements. One classic study focused on applying a force perpendicular to a canine long axis with a parabolic shaped root, obtaining the Burstone formula ($M:F = 0.068 \times h^2/y$), where h is the distance from the alveolar crest to the apex and y is the distance between the C_{RES} and the C_{ROT}.[5]

A previous study demonstrated a nonlinear relationship between tooth movement and force system directions and that the Burstone formula must be modified depending on them. In addition, different types of nonlinear behavior depend on the applied force and moment directions. This behavior was demonstrated for an upper first premolar with average dimension.[10]

The hypothesis of the current article was that this phenomenon is due to root asymmetries and specific differences in tooth morphology. The purpose was to describe which tooth morphological characteristics determine this nonlinear behavior and statistically test if tooth movement in any direction can be predicted if data on root morphology and the original force system are provided to the orthodontist.

The specific objective was to determine the relationships between all meaningful permutations of M:F and

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Table 1. Tooth Dimensions for the Two Data Sets

	MD, mm	LB, mm	Root Length Plane YZ, mm	Root Length Plane ZX, mm	Root AVG, mm
Patient 1					
Maxillary central incisor	6.1	5.8	15.6	16.2	15.9
Maxillary lateral incisor	4.2	5.8	15.1	15.5	15.3
Maxillary canine	6.2	8.8	15.8	16.0	15.9
Maxillary first premolar	4.9	8.7	13.6	14.2	13.9
Maxillary second premolar	5.4	8.4	14.4	14.3	14.4
Maxillary first molar	7.2	9.0	13.1	12.8	13.0
Maxillary second molar	7.8	10.1	12.5	12.0	12.3
Mandibular central incisor	4.3	6.2	13.1	14.0	13.6
Mandibular lateral incisor	3.9	6.3	12.2	12.9	12.6
Mandibular canine	3.9	5.9	12.5	14.0	13.3
Mandibular first premolar	4.8	6.9	10.8	11.7	11.3
Mandibular second premolar	4.9	7.0	13.8	14.2	14.0
Mandibular first molar	9.2	9.5	11.8	12.0	11.9
Mandibular second molar	9.2	8.2	11.6	12.1	11.9
Patient 2					
Maxillary central incisor	6.9	7.4	13.7	15.8	14.7
Maxillary lateral incisor	4.8	6.4	12.0	13.6	12.8
Maxillary canine	6.2	7.4	16.0	16.4	16.2
Maxillary first premolar	5.5	8.4	12.3	13.3	12.8
Maxillary second premolar	6.1	8.9	13.2	13.8	13.5
Maxillary first molar	8.8	8.8	11.4	12.2	11.8
Maxillary second molar	9.2	10.8	13.2	12.8	13.0
Mandibular central incisor	3.8	5.6	11.4	12.1	11.8
Mandibular lateral incisor	3.5	5.5	10.6	11.5	11.1
Mandibular canine	3.5	5.3	10.9	12.1	11.5
Mandibular first premolar	4.4	6.2	9.4	10.1	9.8
Mandibular second premolar	4.3	6.3	12.0	12.3	12.2
Mandibular first molar	8.1	8.3	10.2	10.4	10.3
Mandibular second molar	8.1	7.3	10.1	10.5	10.3

the C_{ROT}, for different force directions, in each spatial plane (XY, YZ, ZX), for each tooth. Through finite element analysis (FEA), comparative maps of the effects of relevant M:F combinations on each tooth were built. Then, the statistical evaluation of the resulting maps was used to determine if tooth morphological features could be used to predict how the tooth will move with a specific force system. The significance of this result, under the limitations of the method, is that a clinician could derive the biomechanical behavior of any tooth if the force system and tooth dimensions are given, without having to resort to FEA.

To complete the tooth movement laws, the aim was to retrieve a statistically based 3D mathematical relationship between C_{RES} and tooth morphology. The C_{RES} coordinates were analyzed for the previous data set to also introduce a set of covariates to calculate the 3D C_{RES} coordinates based on the tooth dimensions.

MATERIALS AND METHODS

The 3D models for each tooth were obtained from two patients according to the method described by Savignano et al.[10] The teeth dimensions are reported in Table 1. The root dimensions were measured considering the root part attached to the bone through the periodontal ligament (PDL). The Loma Linda University Institutional Review Board (IRB) committee determined that this research did not require IRB approval because data or specimens were not collected specifically for this study and private individually identifiable information were not received.

Each maxillary and mandibular model was manually sliced to obtain seven tooth-PDL-bone multibody models from each arch for the FEA. A total of 28 submodels were extracted. Bone and teeth were modeled as simplified homogenous bodies without discerning between cortical and cancellous bone and enamel, pulp and dentin, as was done also in previous studies because the data differences are insignificant.[9–12] A linear elastic model was used for each structure to test the movements under the assumption of low PDL strains ($<$7.5%),[13] as summarized in Table 2.

The geometries were imported in the Finite Element Software ANSYS Workbench 16 (ANSYS, Canonsburg, Penn), where all the bodies were meshed with solid elements.

The coordinate system was defined for each tooth according to the occlusal plane. The *x*-axis was congruent with the buccolingual tooth dimension,

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Table 2. Material Properties Used for the Finite Element Analysis

Structure	Young Modulus, MPa	Poisson's Ratio
Tooth	20,000	0.3
Bone	2000	0.3
Periodontal ligament	0.05	0.3

whereas the *y*-axis was congruent with the mesiodistal and the *z*-axis was perpendicular to the occlusal plane (Figure 1).

To find the C_{RES}, three simulations were run for each tooth, one for each coordinate plane, applying a moment with the specific values shown in Table 3. The moment amount was different for each tooth because each tooth requires a different load[14] to keep the PDL strain $<$7.5%, allowing for a linear PDL model within this range.[15]

The C_{RES} coordinates were measured with the coordinate system located at the center of the cementoenamel junction (CEJ), as shown in Figure 1. For each tooth, the different M:F tested were applied at the respective C_{RES} to provide a generalized map of tooth movements that could be transferred to any appliance (eg, brackets, aligners).

A tooth-specific constant force was applied at the C_{RES} for each tooth as reported in Table 3, while the M:F varied from $-$12 mm to 12 mm. As for the moment, the forces used during the simulations were also proportionally different for each tooth, so as to keep the same strain $<$7.5% in the PDL for ascertaining the validity of the linear model. All of the bones' nodes were assigned zero displacement to simulate a rigid body due to the transient nature of tooth displacement solely attributed to bone deformation, as reported previously.[9] The simulations were performed on the three spatial planes (plane XY, plane YZ, plane ZX). For each plane, 17 equivalent force systems were applied at the C_{RES} of each tooth, as shown in the example of Figure 2. Figure 3 shows a schematic of the experimental design used for each tooth.

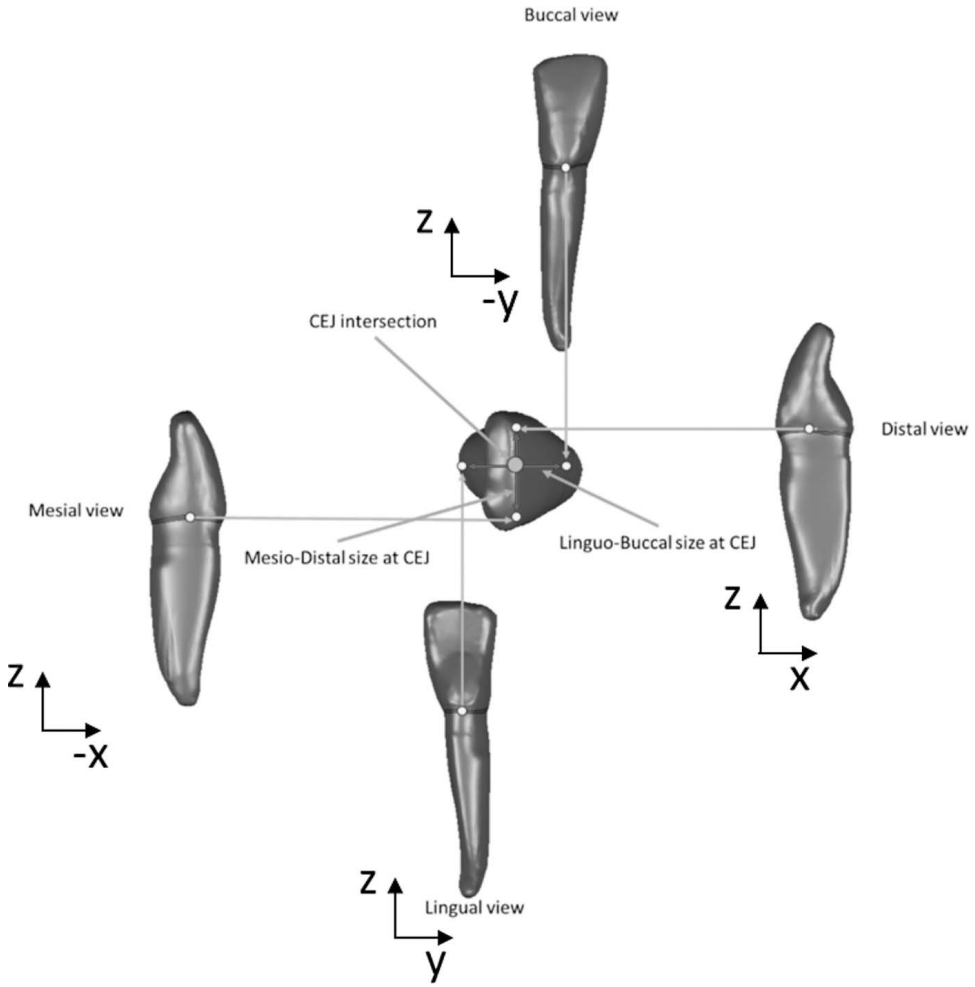

Figure 1. The cementoenamel junction (CEJ) intersection (yellow) used to refer the C_{RES} coordinates was defined on the plane XY as the intersection between the mesiodistal and the linguobuccal tooth dimensions. On the *z*-axis, the coordinate system was located at the average between CEJ on the mesiodistal views and CEJ on the linguobuccal views.

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Table 3. Moment and Forces Applied to Each Tooth to Locate the Approximate Center of Resistance, Keeping the PDL Principal Strain Value Below 7.5%

	Central Incisor	Lateral Incisor	Canine	First Premolar	Second Premolar	First Molar	Second Molar
Moment, Nmm							
Maxillary	−1.8	−1.08	−1.68	−1.56	−1.56	−2.88	−3
Mandibular	−1.08	−1.08	−1.44	−1.44	−1.56	−2.76	−2.28
Force, N							
Maxillary	0.15	0.09	0.14	0.13	0.13	0.24	0.25
Mandibular	0.09	0.09	0.12	0.12	0.13	0.23	0.19

The projected axis of rotation (C_{ROT}) was evaluated for each scenario through the displacement vectors of two nodes of the tooth.[8] The resulting C_{ROT} coordinates and the distances from the C_{RES} were evaluated and analyzed to obtain a mathematical relationship between M:F and C_{ROT}. The D (distance $C_{RES} - C_{ROT}$) vs M:F was analyzed using CurveExpert Basic software (CurveExpert, Madison, Ala), dividing the analysis by tooth and spatial plane. The starting model was set as simple hyperbolic, as previously validated for different teeth:

$$D_{C.Res-C.Rot} = \frac{k}{MF}$$

Statistical analyses were performed with the aim of obtaining generalized formulae to locate the tooth C_{RES} and calculate an approximate k for every tooth and force system.

Multiple linear regression analysis was conducted to assess the influence of the teeth morphological data reported in Table 1 for the first data set. All hypotheses were tested at an $\alpha = .05$ level for the second k data set. A sample size of two patients was considered appropriate for a pilot study. For statistical analysis, normality was assumed for the data even if it could not be proven because of the sample size, and the bootstrap method was applied for coefficient convergence. Multicollinearity between the independent variables was tested, discarding variables with variance inflation factor >1.5.

To evaluate the performance of the regression models, the covariates were tested on a randomly chosen tooth: a mandibular central incisor was reconstructed through a combination of cone-beam computed tomography (CBCT) and optical scanner for this purpose. The process shown in Figure 3 was

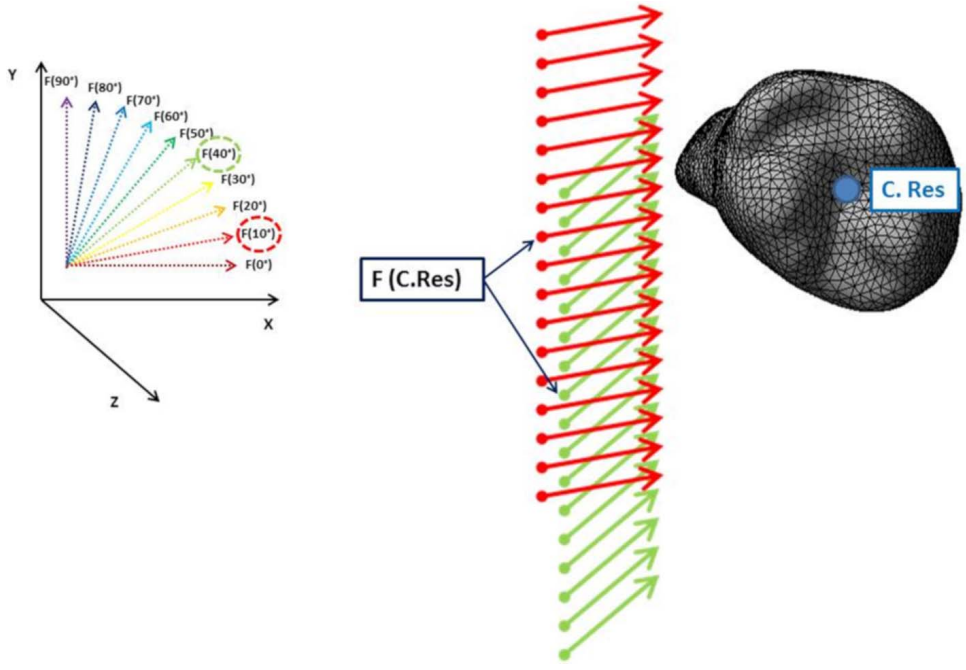

Figure 2. Example, plane XY, representation of the incremental directional force system changes (left) and correspondent force systems tipped 10° and 40° with respect to the *x*-axis for a maxillary first molar (right). Each of the different force and moment combinations at the C_{RES} was equivalent to one of the 17 single forces spaced 2 mm or 1 mm from each other, where the central force is applied at the C_{RES}. The higher resolution force increment (1 mm) was applied in the region M:F = [−4:4]. To vary directions, the force was constant, but its direction for each position was changed in the spatial plane of interest in 10° increments, resulting in 10 different simulations for each M:F value at the C_{RES}.

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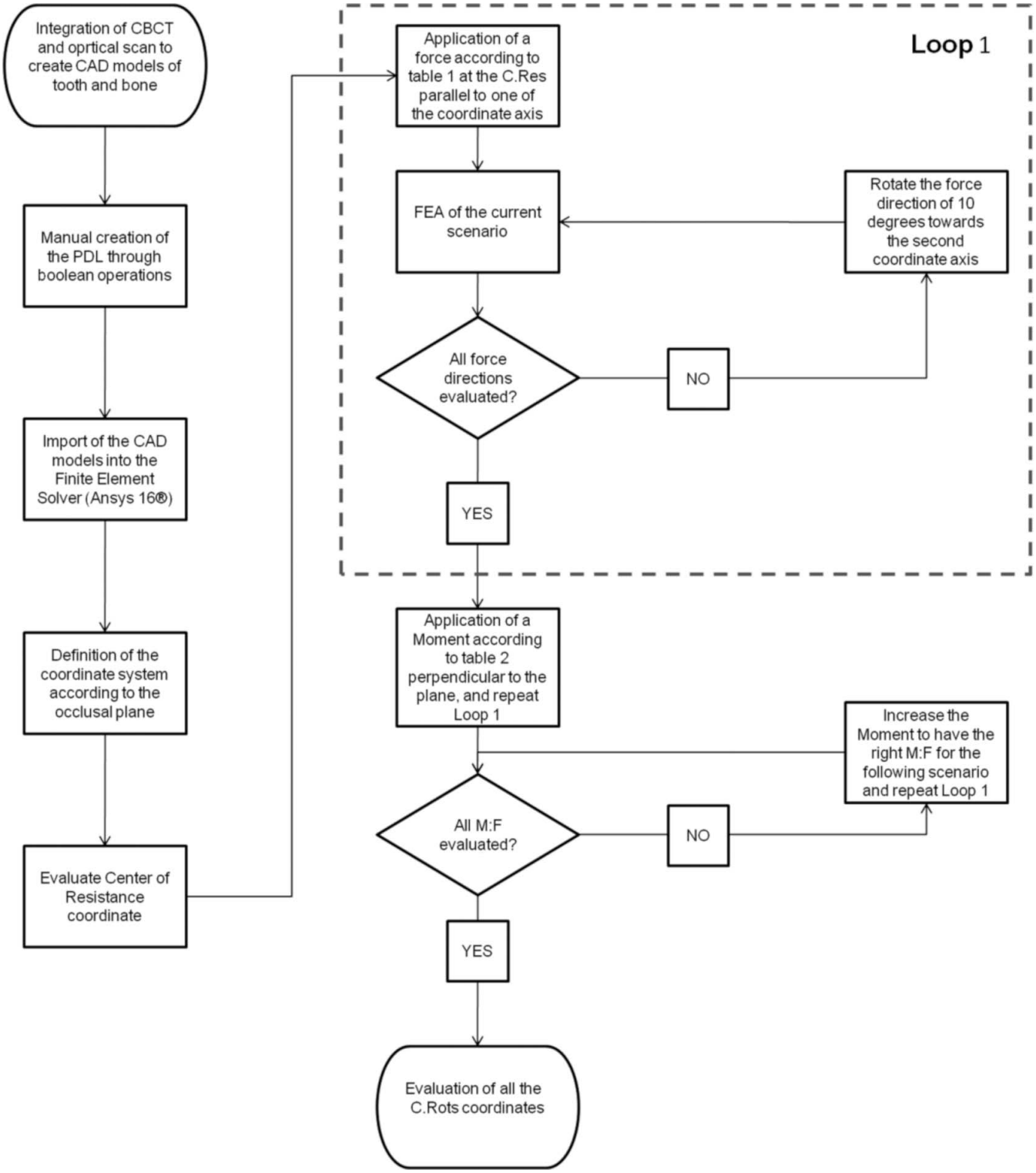

Figure 3. Experiment workflow.

applied to the tooth to calculate its k values. Then, the C_{RES} coordinates and k values were derived using the covariates obtained by the regression models, and the two FEA data sets were then compared.

RESULTS

The statistical analysis demonstrated that the C_{RES} coordinates can be calculated using the set of covariates shown in Table 4 at a significance level of

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Table 4. C_{RES} Coefficients for Each Tooth[a]

Coordinate	Arch	Coefficient	Unstandardized Coefficients	Significance	95.0% Confidence Interval for B	
			B		Lower Bound	Upper Bound
X	Mandibular	(Constant)	0.023	.983	−2.273	2.318
		MD (mm)	0.186	.214	−0.125	0.496
		LB (mm)	−0.090	.730	−0.647	0.468
	Maxillary	(Constant)	0.733	.558	−1.936	3.403
		MD (mm)	−0.285	.177	−0.720	0.150
		LB (mm)	0.210	.306	−0.221	0.642
Y	Mandibular	(Constant)	1.493	.007	0.489	2.497
		LB (mm)	−0.258	.002	−0.404	−0.111
	Maxillary	(Constant)	−0.218	.813	−2.180	1.744
		LB (mm)	0.014	.896	−0.222	0.250
Average Z	Mandibular	(Constant)	0.112	.886	−1.569	1.793
		R_{YZ} (mm)	0.793	.005	0.301	1.286
		R_{ZX} (mm)	−1.164	.000	−1.625	−0.703
	Maxillary	(Constant)	1.529	.194	−0.901	3.959
		R_{YZ} (mm)	0.122	.471	−0.238	0.482
		R_{ZX} (mm)	−0.618	.002	−0.965	−0.271

[a] LB indicates linguobuccal dimension at the cementoenamel junction (CEJ); MD, mesiodistal dimension at the CEJ; R_{YZ}, root length on the plane YZ; R_{ZX}, root length on the plane ZX. The predictors used to calculate the C_{RES} are the unstandardized coefficients.

.05. Different equations were found for each spatial coordinate stratified by maxillary and mandibular teeth. The statistical analysis showed that k can be predicted by using the root dimensions, the force direction, and the spatial plane, as hypothesized.

The results also might imply that a different set of covariates should be considered for each plane, with additional distinction placed upon the tooth morphology.

The width of the 95% confidence intervals for the k covariates varied considerably and lack the power to be considered as reliable for several of the coefficients.

Each hyperbolic equation was characterized by the constant of proportionality (k), which depended on the plane, the force's direction, and the tooth (Table 5), as classically defined by Burstone[5] and generalized in 3D by Savignano and Viecilli.[10]

Figure 4 shows the k shapes for the first patient and indicated that k increased greatly when the force direction became parallel to the tooth long axis (*z*-axis). In addition, the k values were larger on the YZ and ZX planes than on the XY plane, which contained the mesiodistal and buccolingual dimensions of the teeth. These findings generalized for every tooth confirmed the results obtained by a previous study on a first maxillary premolar.[10]

After calculating the C_{ROT} location for all of the different load systems, it was confirmed that the M:F and the $D_{(C_{RES}-C_{ROT})}$ had an hyperbolic relationship in every tooth, characterized by the parameter k, which changed for each tooth and each force system.

The k variability was different among different teeth and among different planes for the same tooth. The analysis of the k values on the different planes showed that they depended not only on the force direction but also on the moment direction.

K could be predicted with the set of covariates shown in Table 5 at a statistically significant level ($P <$ .05). It was possible to retrieve different equations for each tooth and planes, and hence, it was possible to estimate k for every tooth in any direction in this manner.

A random mandibular central incisor was chosen to show the covariates' efficacy.

Table 6 and Figure 5 show the k data sets obtained on a random mandibular central incisor through FEA and morphological covariates, respectively.

DISCUSSION

The relationship between M:F and initial tooth movement was previously investigated by other researchers. The limitation of the previous studies[2,5–7,9,16] was that they did not relate the effect of M:F variations with tooth morphology, thus making it a necessary requirement to run additional and advanced computations to obtain tooth response curves. Only one study showed in two different teeth that they had a different orthodontic response to M:F variations.[7] This study, although providing more comprehensive 3D data, also had a limitation, which was the simplified linear PDL model. This choice was justified because the loads modeled were below the strain threshold where the PDL starts to stiffen. In a PDL nonlinear model, the responses and k values would likely be different for different loads.[15]

The statistical analysis provided a set of covariates to calculate the C_{RES} coordinates and an approximate

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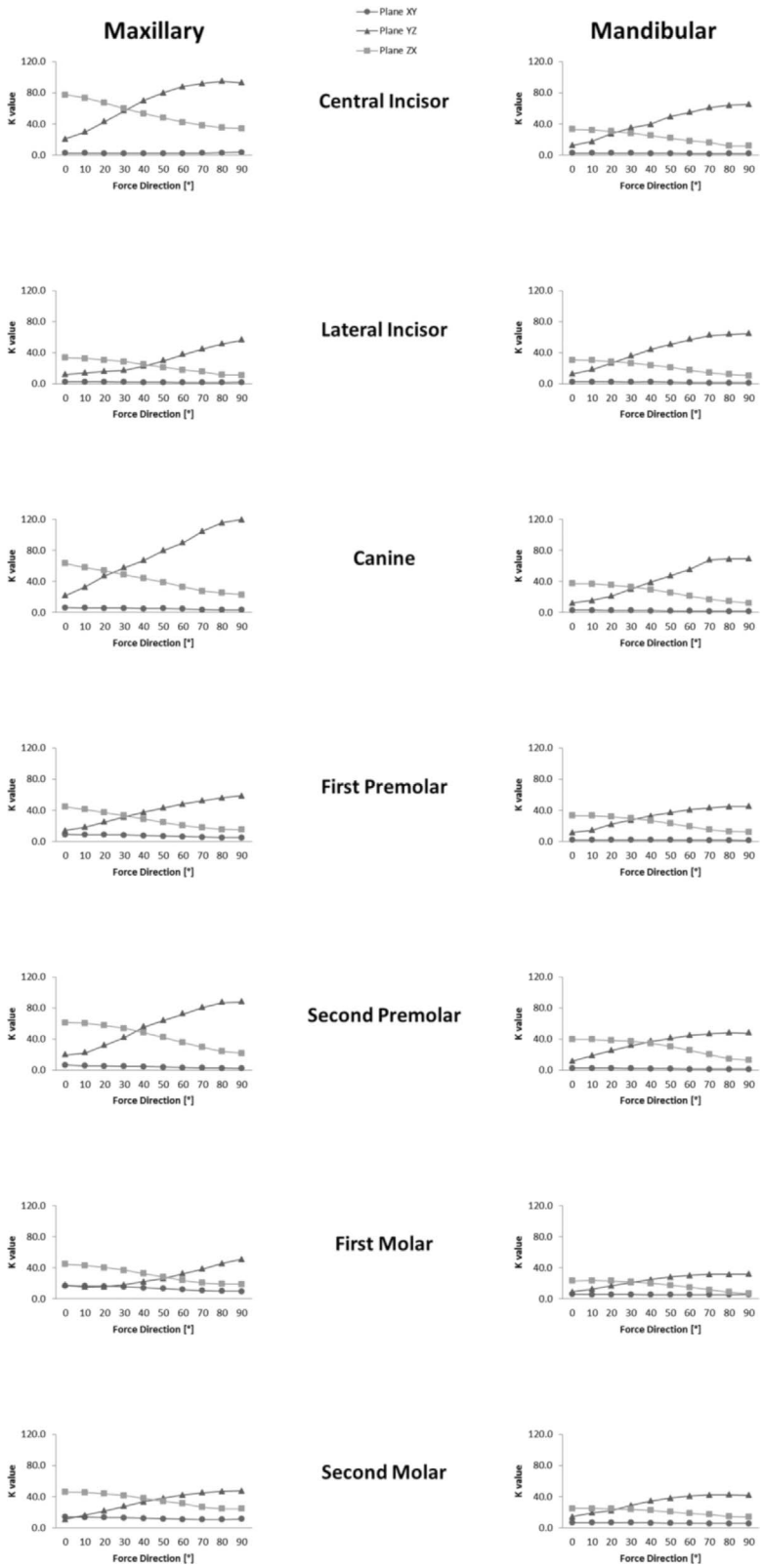

Figure 4. Graphical representation of k vs force direction for each tooth on the different planes for patient 1. The force direction is reported on the horizontal axis and the k value on the vertical axis. The direction is referred as the angle between the force and the first coordinate axis for each plane.

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Table 5. k Coefficients for Each Tooth[a]

			Unstandardized Coefficients		95.0% Confidence Interval for B	
Tooth	Plane	Model	B	Significance	Lower Bound	Upper Bound
LR1	XY	(Constant)	−2.925	.000	−3.799	−2.051
		R_{YZ}, mm	0.436	.000	0.366	0.506
		Angle, °	−0.012	.000	−0.014	−0.010
	YZ	(Constant)	70.928	.002	32.288	109.568
		Angle, °	0.642	.000	0.547	0.738
		R_{AVG}, mm	−4.224	.010	−7.226	−1.221
	ZX	(Constant)	94.826	.000	67.200	122.452
		R_{YZ}, mm	−4.309	.001	−6.511	−2.107
		Angle, °	−0.353	.000	−0.418	−0.288
LR2	XY	(Constant)	−2.726	.009	−4.619	−0.834
		Angle, °	−0.018	.000	−0.022	−0.013
		R_{ZX}, mm	0.453	.000	0.294	0.613
	YZ	(Constant)	11.913	.003	5.196	18.629
		Angle, °	0.641	.000	0.524	0.758
	ZX	(Constant)	1.727	.827	−15.892	19.346
		Angle, °	−0.269	.000	−0.303	−0.236
		R_{ZX}, mm	2.457	.004	1.056	3.858
LR3	XY	(Constant)	−0.172	.651	−1.031	0.688
		Angle, °	−0.017	.000	−0.019	−0.015
		R_{AVG}, mm	0.240	.000	0.173	0.307
	YZ	(Constant)	9.798	.027	1.454	18.142
		Angle, °	0.707	.000	0.525	0.890
	ZX	(Constant)	−82.169	.000	−102.567	−61.771
		Angle, °	−0.249	.000	−0.286	−0.211
		LB, mm	20.289	.000	16.660	23.919
LR4	XY	(Constant)	−0.084	.775	−0.723	0.554
		Angle, °	−0.007	.000	−0.009	−0.006
		R_{AVG}, mm	0.193	.000	0.132	0.253
	YZ	(Constant)	−39.448	.029	−74.123	−4.772
		Angle, °	0.370	.000	0.316	0.423
		MD, mm	11.431	.006	3.940	18.922
	ZX	(Constant)	35.153	.000	32.975	37.331
		Angle, °	−0.257	.000	−0.299	−0.216
LR5	XY	(Constant)	−3.723	.002	−5.708	−1.737
		Angle, °	−0.013	.000	−0.019	−0.008
		R_{ZX}, mm	0.466	.000	0.321	0.610
	YZ	(Constant)	12.244	.000	8.866	15.623
		Angle, °	0.502	.000	0.434	0.569
	ZX	(Constant)	45.015	.000	41.798	48.232
		Angle, °	−0.342	.000	−0.406	−0.278
LR6	XY	(Constant)	−3.485	.014	−6.076	−0.893
		Angle, °	−0.009	.009	−0.015	−0.003
		LB, mm	0.988	.000	0.697	1.278
	YZ	(Constant)	−30.629	.004	−48.991	−12.267
		Angle, °	0.258	.000	0.216	0.300
		LB, mm	4.484	.000	2.459	6.509
	ZX	(Constant)	25.996	.000	23.653	28.339
		Angle, °	−0.210	.000	−0.249	−0.172
LR7	XY	(Constant)	−17.535	.000	−19.435	−15.634
		Angle, °	−0.018	.000	−0.023	−0.013
		R_{AVG}, mm	2.070	.000	1.902	2.237
	YZ	(Constant)	21.989	.000	16.981	26.996
		Angle, °	0.221	.001	0.117	0.325
	ZX	(Constant)	−5.848	.102	−13.038	1.341
		R_{YZ}, mm	2.834	.000	2.176	3.491
		Angle, °	−0.147	.000	−0.165	−0.130

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Table 5. Continued

			Unstandardized Coefficients		95.0% Confidence Interval for B	
Tooth	Plane	Model	B	Significance	Lower Bound	Upper Bound
UR1	XY	(Constant)	2.404	.000	1.938	2.869
		Angle, °	−0.003	−0.483	−0.012	0.006
	YZ	(Constant)	125.133	.007	45.987	204.280
		Angle, °	0.910	.000	0.754	1.065
		MD, mm	−16.136	.021	−29.082	−3.190
	ZX	(Constant)	191.353	.000	156.300	226.407
		Angle, °	−0.505	.000	−0.575	−0.434
		MD, mm	−18.964	.000	−24.273	−13.656
UR2	XY	(Constant)	11.043	.000	9.485	12.601
		Angle, °	−0.012	.000	−0.014	−0.009
		LB, mm	−1.389	.000	−1.646	−1.132
	YZ	(Constant)	68.928	.000	37.845	100.012
		Angle, °	0.490	.000	0.427	0.554
		R_{ZX}, mm	−3.791	.002	−5.932	−1.650
	ZX	(Constant)	−75.939	.011	−129.368	−22.511
		Angle, °	−0.330	.000	−0.419	−0.241
		LB, mm	19.624	.001	10.818	28.430
UR3	XY	(Constant)	−1.744	.027	−3.260	−0.228
		Angle, °	−0.031	.000	−0.035	−0.027
		LB, mm	0.904	.000	0.717	1.091
	YZ	(Constant)	28.181	.000	17.933	38.429
		Angle, °	1.074	.000	0.885	1.262
	ZX	(Constant)	61.654	.000	56.214	67.094
		Angle, °	−0.492	.000	−0.588	−0.396
UR4	XY	(Constant)	28.903	.000	23.958	33.848
		Angle, °	−0.037	.000	−0.048	−0.026
		MD, mm	−4.123	.000	−5.077	−3.170
	YZ	(Constant)	−46.292	.044	−90.973	−1.610
		Angle, °	0.578	.000	0.548	0.608
		LB, mm	6.891	.016	1.685	12.098
	ZX	(Constant)	68.744	.000	54.613	82.875
		Angle, °	−0.321	.000	−0.347	−0.295
		MD, mm	−5.287	.001	−8.000	−2.574
UR5	XY	(Constant)	−25.264	.000	−31.561	−18.967
		Angle, °	−0.034	.000	−0.041	−0.027
		R_{AVG}, mm	2.182	.000	1.733	2.632
	YZ	(Constant)	20.307	.000	16.277	24.337
		Angle, °	0.810	.000	0.735	0.885
	ZX	(Constant)	65.308	.000	62.962	67.654
		Angle, °	−0.467	.000	−0.509	−0.424
UR6	XY	(Constant)	18.281	.000	16.896	19.666
		Angle, °	−0.116	.000	−0.140	−0.092
	YZ	(Constant)	−20.170	.188	−52.002	11.663
		Angle, °	0.464	.000	0.351	0.577
		MD, mm	3.969	.048	0.034	7.905
	ZX	(Constant)	355.044	.001	173.584	536.504
		Angle, °	−0.291	.000	−0.360	−0.221
		LB, mm	−34.624	.003	−55.026	−14.223
UR7	XY	(Constant)	−6.120	.157	−14.954	2.713
		R_{YZ}, mm	1.676	.000	0.989	2.364
		Angle, °	−0.072	.000	−0.082	−0.062
	YZ	(Constant)	161.592	.000	99.350	223.833
		Angle, °	0.346	.000	0.268	0.423
		LB, mm	−14.270	.000	−20.236	−8.304
	ZX	(Constant)	193.416	.000	155.396	231.436
		Angle, °	−0.240	.000	−0.279	−0.201
		R_{AVG}, mm	−12.016	.000	−15.036	−8.996

[a] LB indicates linguobuccal dimension at the cementoenamel junction (CEJ); MD, mesiodistal dimension at the CEJ; R_{YZ}, root length on the plane YZ; R_{ZX}, root length on the plane ZX; R_{AVG}, average between R_{YZ} and R_{ZX}. The predictors used to calculate k are the unstandardized coefficients.

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Table 6. Comparison of Predicted and Calculated k Values for a Random Mandibular Central Incisor With MD = 3.3 mm[a]

	Center of Resistance	
	Predicted	Calculated
Loc x, mm	0.9	0.5
Loc y, mm	−0.1	−0.1
Loc z, mm	−5.2	−5.5
	k	
Angle, °	Predicted K	Calculated K
Plane XY		
0	2.9	3.4
10	2.8	3.4
20	2.6	3.3
30	2.5	3.1
40	2.4	2.9
50	2.3	2.7
60	2.2	2.4
70	2.0	2.1
80	1.9	1.8
90	1.8	1.5
Plane YZ		
0	14.3	9.2
10	20.7	15.3
20	27.2	19.5
30	33.6	24.3
40	40.0	31.4
50	46.4	42.3
60	52.8	45.8
70	59.3	49.5
80	65.7	55.4
90	72.1	62.2
Plane ZX		
0	37.5	35.7
10	34.0	35.2
20	30.5	33.9
30	26.9	31.9
40	23.4	29.2
50	19.9	24.1
60	16.3	21.0
70	12.8	17.5
80	9.3	14.9
90	5.7	13.3

[a] LB = 5.2 mm, root YZ = 13.3 mm, and root ZX = 13.5 mm.

k for a random tooth, which described the asymmetric mechanical response of every tooth to an applied load, because of the tooth morphology and force system (Figure 6). The root morphology defined the tooth-specific response to an applied force system. This was likely because the PDL is the most deformable structure and approximately follows the root shape, thus being mathematically related to tooth movement. In addition, the root dimensions weigh differently on the response curves depending on the plane on which the movement occurs and on the number of roots. Both factors define the size of the active contact region between the tooth and PDL (the region where the PDL is in tension or compression).

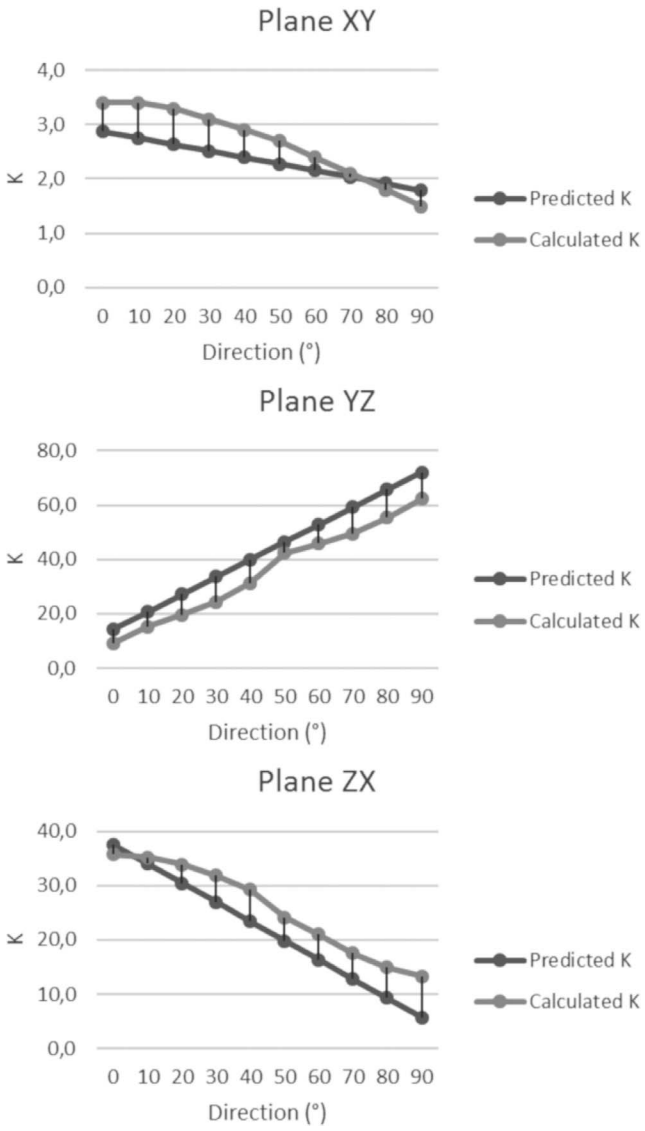

Figure 5. Graphical representation of predicted k vs calculated k for a random mandibular central incisor on each plane.

Orthodontic appliances are usually tested with an electromechanical transducer, capable of measuring in 3D the load system delivered by orthodontic appliances.[17–19] However, the results obtained by transducers cannot be reliably used to predict or approximate the tooth behavior since limited information is available on the different relationship between M:F values and 3D tooth movements for each tooth.

During the evaluation of the appliance's effectiveness, it is recommended to calculate the k for each tooth. Afterward, the errors in the force system delivered to each tooth could be weighted to understand how each error really affected the final expected results, and then a decision can be made as to whether it is an acceptable error or changes are needed in the appliance design.

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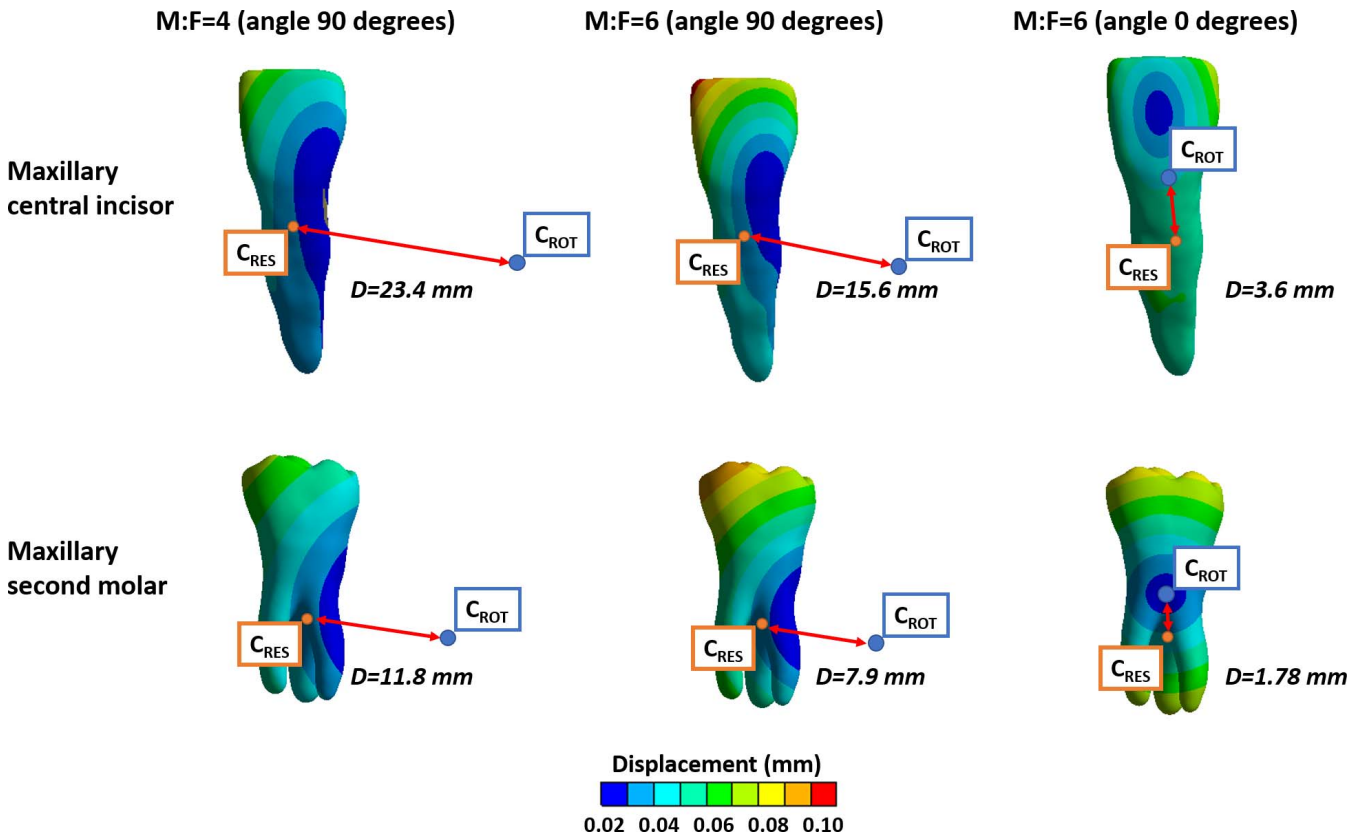

Figure 6. The different incremental changes in C_{ROT} with two M:F values (4 mm and 6 mm) and with two different force directions on the plane YZ for a maxillary central incisor and a maxillary second molar.

It is not practical to calculate k for each tooth using FEA before every orthodontic treatment. Hence, the set of equations provided by the statistical analysis can be used to calculate an approximate k knowing the tooth morphology. In particular, it would be necessary to provide a patient's CBCT to obtain the appropriate variables.

Comparing the results obtained on a random mandibular central incisor through FEA and covariates, respectively, it was noticed that the results were more accurate on the XY (16% average error) than on the ZX plane (26% average error) and on the YZ plane (24% average error). Despite that, the method introduced in the present article showed an overall acceptable accuracy (22% average error), using only the linguobuccal size at the CEJ, mesiodistal size at the CEJ, and root length.

Previous authors have investigated the C_{ROT} location features. Yang and Tang[12] compared the effect of different M:F on the C_{ROT} location for a canine tooth, with and without a bracket. Cattaneo et al.[7] tested different M:F values on a premolar and canine and showed how the C_{ROT} moved closer to the apex with an increase in M:F value.

Provatidis[20] demonstrated that the position of the C_{ROT} was affected by root dimensions, PDL thickness, and material properties. On the other hand, the present study aimed at finding a generalized set of predictors for every tooth to estimate C_{RES} and C_{ROT} locations, which will allow comparison of the effect of different orthodontic appliances in 3D. The estimation of the expected C_{RES} and C_{ROT} coordinates for each scenario could be helpful to easily understand which appliance design provides the best expected movement.

It could be desirable to develop a set of equations that require only tooth crown features and features retrievable by a panoramic radiograph, but it would evidently result in more error. This would allow calculation of the k data set for a random tooth using a less invasive method based on an optical scan and less radiation.

CONCLUSIONS

- The current study showed that it is possible to estimate the approximate C_{RES} coordinates and the entire tooth movement curve for the initial phase of orthodontic movement, knowing the root dimensions, using separate equations for maxillary and mandibular teeth.

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- The results showed that variations of the M:F have a different influence depending on the tooth morphology and the force system features, and the k values are comprised between 1 and 119.4. Therefore, those differences cannot be neglected when estimating tooth movement response curves.
- The geometrical features necessary to calculate k are linguobuccal size at the CEJ, mesiodistal size at the CEJ, root length on the ZX plane, root length on the YZ plane, and average root length. All of these dimensions can be measured using CBCT.
- Using k, it is possible to estimate the distance between the expected C_{ROT} and the C_{ROT} obtained by any force system applied to a tooth. This method allows quantification of the potential effectiveness of any orthodontic appliance and selection of the most appropriate one. It is necessary to determine the desired orthodontic movement (expected C_{ROT}), the force system delivered by the appliance under examination (actual C_{ROT}), and the tooth morphology.
- Further studies should analyze a larger data set and attempt to apply the same method for the whole orthodontic movement, while also accounting for nonlinear PDL behavior.

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