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Nonlinear dependency of tooth movement on force system directions

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Introduction: Moment-to-force ratios (M:F) define the type of tooth movement. Typically, the relationship between M:F and tooth movement has been analyzed in a single plane. Here, to improve the 3-dimensional tooth movement theory, we tested the hypothesis that the mathematical relationships between M:F and tooth movement are distinct, depending on force system directions. **Methods:** A finite element model of a maxillary first premolar, scaled to average tooth dimensions, was constructed based on a cone-beam computed tomography scan. We conducted finite element analyses of the M:F and tooth movement relationships, represented by the projected axis of rotation in each plane, for 510 different loads. **Results:** We confirmed that a hyperbolic equation relates the distance and M:F; however, the constant of proportionality ("k") varied nonlinearly with the force direction. With a force applied parallel to the tooth's long axis, "k" was 12 times higher than with a force parallel to the mesiodistal direction and 7 times higher than with a force parallel to the buccolingual direction. **Conclusions:** The M:F influence on tooth movement depends on load directions. It is an incomplete parameter to describe the quality of an orthodontic load system if it is not associated with force and moment directions. (Am J Orthod Dentofacial Orthop 2016;149:838-46)

Evaluating the effectiveness of the loads delivered by an orthodontic device onto the teeth is a challenging task. Complex load systems that act simultaneously in all 3 spatial planes are expected during orthodontic treatment. The initial analysis of relationships between 3-dimensional (3D) tooth movement and loads is possible by discrimination of moment-to-force ratios (M:F) in each planar projection. In 3 dimensions, each M:F is defined by combinations of the forces contained in the plane and the moments perpendicular to it. Unfortunately, even if all information is provided to an orthodontist about the 3D force system on a specific tooth, extremely limited 3D information is currently available on how the tooth will actually move. This occurs because studies on the relationship between M:F and the center (axis) of rotation (C.Rot) are typically limited to 1 plane and 1 force direction. Because of the morphologic asymmetry of teeth, it is reasonable to hypothesize that each 3D permutation of M:F in a different direction has a different mathematical relationship with the patterns of tooth movement.

The most common method to describe the type of tooth movement consists of measuring the distance from the tooth's projected axis of rotation (C.Rot) to the virtual intersection of the axes of resistance (center of resistance [C.Res]). Previous authors have evaluated the influence of controlled M:F increments on the type of tooth movement in 1 plane. One study focused on applying a force perpendicular to a canine's long axis with a parabola-shaped root, obtaining the so-called Burstone[1] formula (M:F = 0.068* h^2/D), where h is the distance from the alveolar crest to the apex, and D is the distance between the C.Res and the C.Rot. Authors of all previous finite element studies[2-4] have analyzed the movement in a single plane, except for Viecilli et al,[5] who analyzed loads in the 3 planes and how they affect the axes of resistance.[5] One experiment[3] studied the maxillary premolar and canine, evaluating the effects of different M:F under constant force and of different forces under constant M:F. The authors found that the force value influences the type tooth

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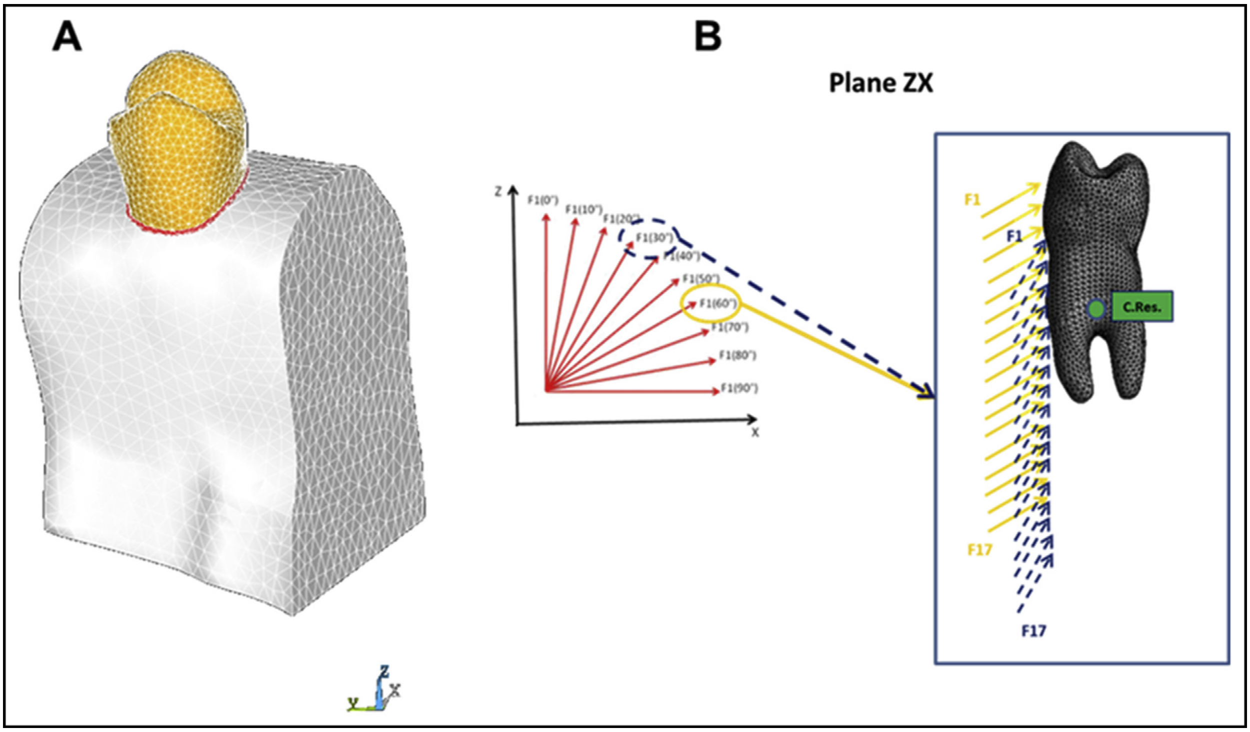

Fig 1. A, The dentoalveolar complex of the maxillary first premolar meshed with tetrahedral elements. The nodes at the interfaces between tooth and PDL and between PDL and bone were shared between the contiguous bodies. The coordinate system was defined according to the occlusal plane. The z-axis is defined as perpendicular to the occlusal plane. The y-axis is parallel to the occlusal plane and approximately congruent with the mesiodistal direction of the tooth. The x-axis is parallel to the occlusal plane and congruent with the palatobuccal direction of the tooth. **B,** Example of the ZX planar representation of the incremental directional force system changes (*left*) and correspondent force systems tipped 30° and 60° with respect to the y-axis (*right*). Each different force and moment combination at the C.Res was equivalent to 1 of the 17 single forces spaced 2 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]. The direction of the force for each position was changed in the coordinate plane of interest in 10° increments, resulting in 10 different simulations for each M:F value at the C.Res.

movement; ie, even with the same M:F, movement is different if the force increases. This happens because of the nonlinear behavior of the periodontal ligament (PDL), which becomes important after a certain strain threshold.[6]

Here, we tested the hypothesis that the mathematical relationships between M:F and tooth movement are distinct, depending on the force direction. To do so, we built a comparative map of the effects of relevant M:F combinations on a maxillary first premolar that can also be useful to help plan tooth movement.

Table I. Tooth dimensions and bracket and C.Res locations with respect to the incisal edge

Dimensions and locations	*Tooth length (mm)*	*Root length (mm)*	*Mesiodistal size at CEJ (mm)*	*Linguobuccal size at CEJ (mm)*
Dimension	20.5	16.2	4.9	8.7
Bracket and C.Res location	X	Y	Z	
Bracket	−2.5	0.2	−4.5	
C.Res	1.4	0.2	−14.4	

CEJ, Cementoenamel junction.

MATERIAL AND METHODS

A model composed of tooth, ligaments, and alveolar bone structures was created by digital integration of a cone-beam computed tomography (CBCT) scan and a surface-structured light scan.[7] An optical scanner was used to reconstruct the tooth crown by digitalization of the plaster casts. The 3D individual dental tissues