A three-dimensional finite element analysis of the effect of archwire characteristics on the self-ligating orthodontic tooth movement of the canine

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Abstract.
BACKGROUND: In orthodontics, the tooth movement is a biologic reaction to applied force systems, brackets, archwires, and periodontium tissue.
OBJECTIVE: To investigate the effects of the various archwire characteristics like the friction coebetween bracket and archwire, the cross-section shape, and the cross-section dimension, on the displacement and the periodontal ligament (PDL) stresses of canine's movement in a self-ligating treatment using the finite element (FE) analysis method.
METHODS: Models of teeth and their supporting tissues, brackets and archwires were constructed. Ten kinds of archwires were used for the simulation.
RESULTS: Considering the translation movement, the maximum displacement, highest stress, and R_{cr} increased with an increase in the cross-section area. The maximum displacement and highest stress increased with an increase in the friction coefficient. The R_{cr} values increased with an increase in the friction coefficient in the round archwires, while decreased with an increase in the rectangular archwires. However, these change tends were different in rotation and inclination movement.
CONCLUSION: The archwire characteristics (round archwire, rectangular archwire, cross-section area, and friction coefficient) exhibited different effects on the tooth translation, rotation, and inclination. Our results can assist in the improvement of the self-ligating orthodontic treatment.

Keywords: Finite element method, archwire shape, cross-section area, friction coefficient, tooth movement

1. Introduction

When sliding mechanics are used in the orthodontic treatment, the frictional force between the bracket and the archwire can influence the force transmitted to the teeth, and thus reduce the accuracy and efficiency of the orthodontic tooth movement [1]. Many studies have investigated this friction *in vitro*. For example, Seo et al. [2] evaluated the effects of the tooth displacement and vibration on the frictional force. Cacciafesta et al. [3] reported that the frictional forces between the ceramic brackets and the stainless-steel brackets increased with an increase in the wire size. Park et al. [4] proposed a new measuring method for measuring the frictional force the between lingual brackets and the archwires. Cacciafesta et al. [5] found that the beta-titanium archwires exhibited a high friction, while stainless steel and nickel-titanium archwires showed a similar friction.

Table 1
Cross section and dimensions of the archwire (inch)

Archwire number	Circular (diameter)	Archwire number	Rectangular
1	0.012	6	0.016 × 0.019
2	0.014	7	0.016 × 0.022
3	0.016	8	0.016 × 0.025
4	0.019	9	0.019 × 0.025
5	0.020	10	0.020 × 0.025

(a)   (b)   (c)
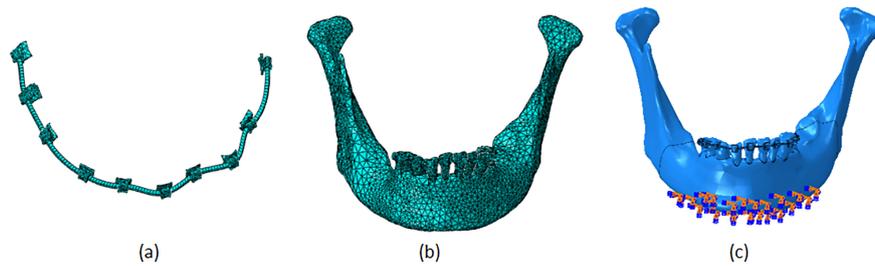
Fig. 1. FE model of bracket and archwire (a), FE model of periodontium tissue (b), and the assembly model and boundary condition (c).

The result of the biological response in the periodontium causes an orthodontic movement of the tooth [6]. However, there are very few investigations on the mechanical stress, particularly those that consider the connection between the frictional forces of the sliding mechanics and orthodontic tooth movement. Evaluation of the stress distributions and the three-dimensional (3D) displacement with an irregular geometry and physical properties is possible using the finite element method (FEM) [7].

Therefore, the current work aims to determine the influence of the friction in the mandibular canine tooth movement and stress distribution during the mandibular canine translation, tipping, and rotation tooth movements using the 3D FE modeling.

2. Materials and methods

The geometry of the 3D FE models of the mandible consisting of teeth with its PDL and alveolar bone was constructed based on CT scanning (Siemens sensation 16, Siemens, German) images (Fig. 1C). PDL was assumed to be 0.25 mm layers around the root of the teeth, as described by previous studies [8,9]. The passive self-ligating brackets with 0.022 × 0.028-in slot were constructed using SolidWorks. All brackets were located on the facial-axis points. Ten cross-section archwires constructed with SolidWorks is shown in Table 1.

All the constructed solidified models were subjected to FEA in Abaqus. Tetrahedral elements were adopted in the finite element models. The number of nodes and elements for each model are shown in Table 2. FE models with brackets and archwires are shown in Fig. 1. All materials were considered to be isotropic homogeneous elastic materials, and the material parameters were applied to each component, based on previous studies (Table 2) [8–10].

A tied condition was established in the ligament-bone, tooth-ligament, and tooth-bracket interfaces. A Coulomb friction condition was established in the contact interfaces between the archwire and bracket surface. The friction coefficient ranged from 0 to 0.5 with an interval of 0.05. The fixed boundary condition was maintained at the base of the mandible and the two ends of the archwire (Fig. 1).

Table 2
Material properties, element, and node numbers of FE models

Material	Modulus of elasticity/MPa	Poisson's ratio	Number of elements	Number of nodes
Teeth	18600	0.31	15457	26371
Alveolar bone	13700	0.3	51502	80282
PDL	0.68	0.49	12891	26396
Bracket	200000	0.3	6260	2260
Archwire	200000	0.3	142	572

The translation (from labial to lingual side from 0.05 mm to 0.30 mm at 0.05 interval), inclination (the crown incline from labial side to lingual side from 0.5° to 3° at 0.5° interval), and rotation (the distal part moves from labial side to lingual side from 0.5° to 3° at 0.5° interval) involved in this investigation. All kinds of archwire with various friction coefficients were used to simulate translation, inclination, and rotation with different designed displacement magnitudes. A total of 1080 simulations were performed using the Abaqus.

3. Results

The change in trends of the maximum displacement of the canine, the highest stress of the PDL, and the R_{cr} of a single case were displayed because the changes in trends in all cases were very similar. The displacement ratio between the crown apical and root apex (R_{cr}) [11] was evaluation. The larger the R_{cr}, the bodily movement was more likely to the translation or rotation of the canine.

3.1. Translation

The maximum displacement of the canine, the highest stress of the PDL, and the R_{cr} increased with an increase in the cross-section area in the round and rectangular archwires (Fig. 2A and B). In the round archwire cases, all the above assesed parameters increased with an increase in the friction coefficient (Fig. 3A). In the rectangular archwire cases, the maximum displacement and highest stress increased with an increase in the friction coefficient. However, the R_{cr} remained constant with an increase in the friction coefficient (Fig. 3B).

3.2. Rotation

All the assesed parameters decreased with an increase in the cross-section area in the round archwire cases (Fig. 4A). In the rectangular archwire cases, the maximum displacement of the canine and the highest stress of the PDL increased with an increase in the cross-section area (Fig. 4B(a) and (b)). However, R_{cr} remained constant with an increase in the cross-section area (Fig. 4B(c)). In the round archwire cases, all the assesed parameters remained constant with an increase in the friction coefficient (Fig. 5A). However, in the rectangular archwire cases, these parameters had minimal increase or decrease, and the slope was much smaller (Fig. 5B).

3.3. Inclination

In the round archwire cases, the maximum displacement of the canine and the highest stress of the PDL decreased with an increase in the archwire diameter (Fig. 6A). These parameters increased with an
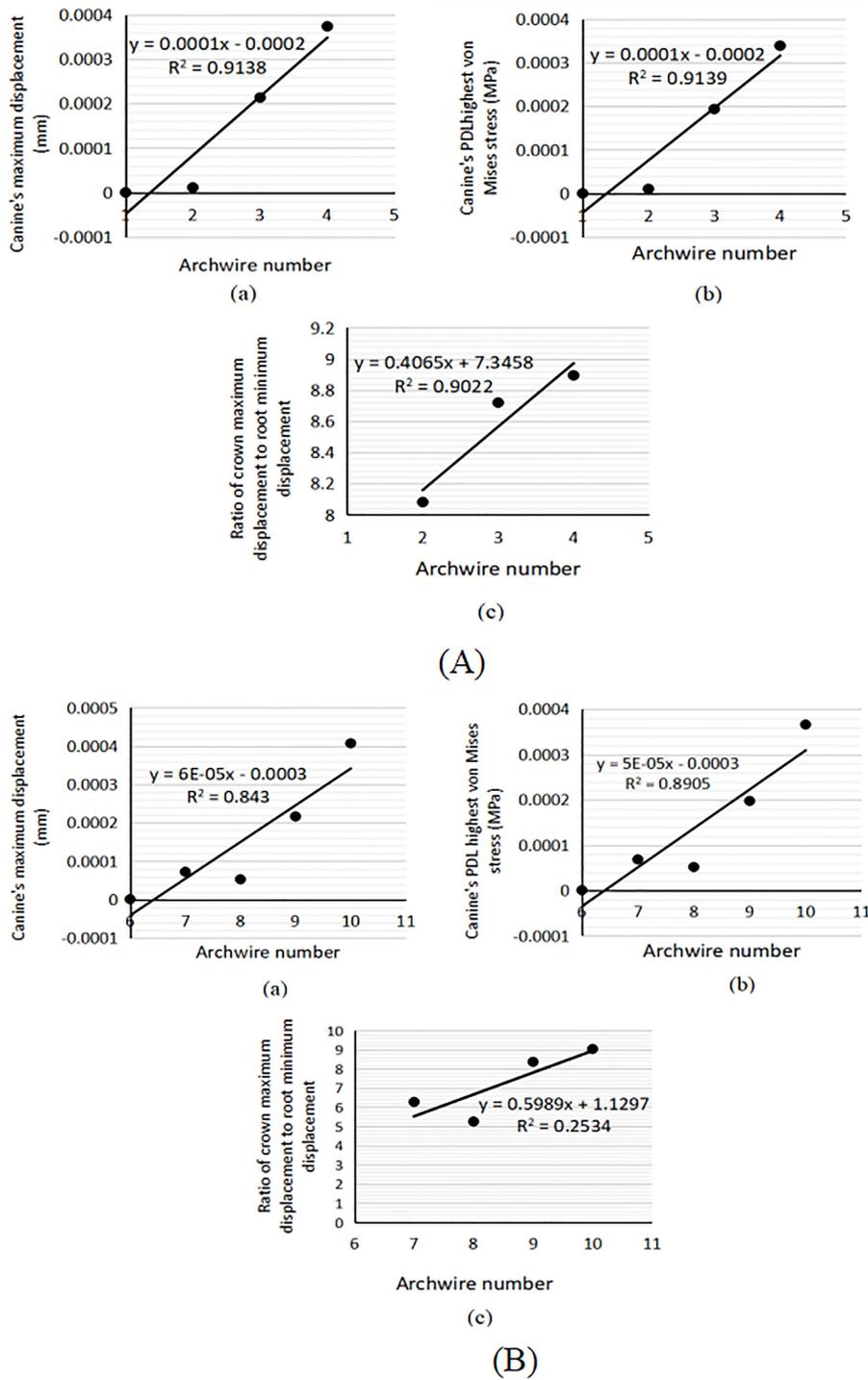
Fig. 2. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); Rcr (c); in translation cases with five round (A) and rectangular archwires (B) and 0.1 friction coefficient.
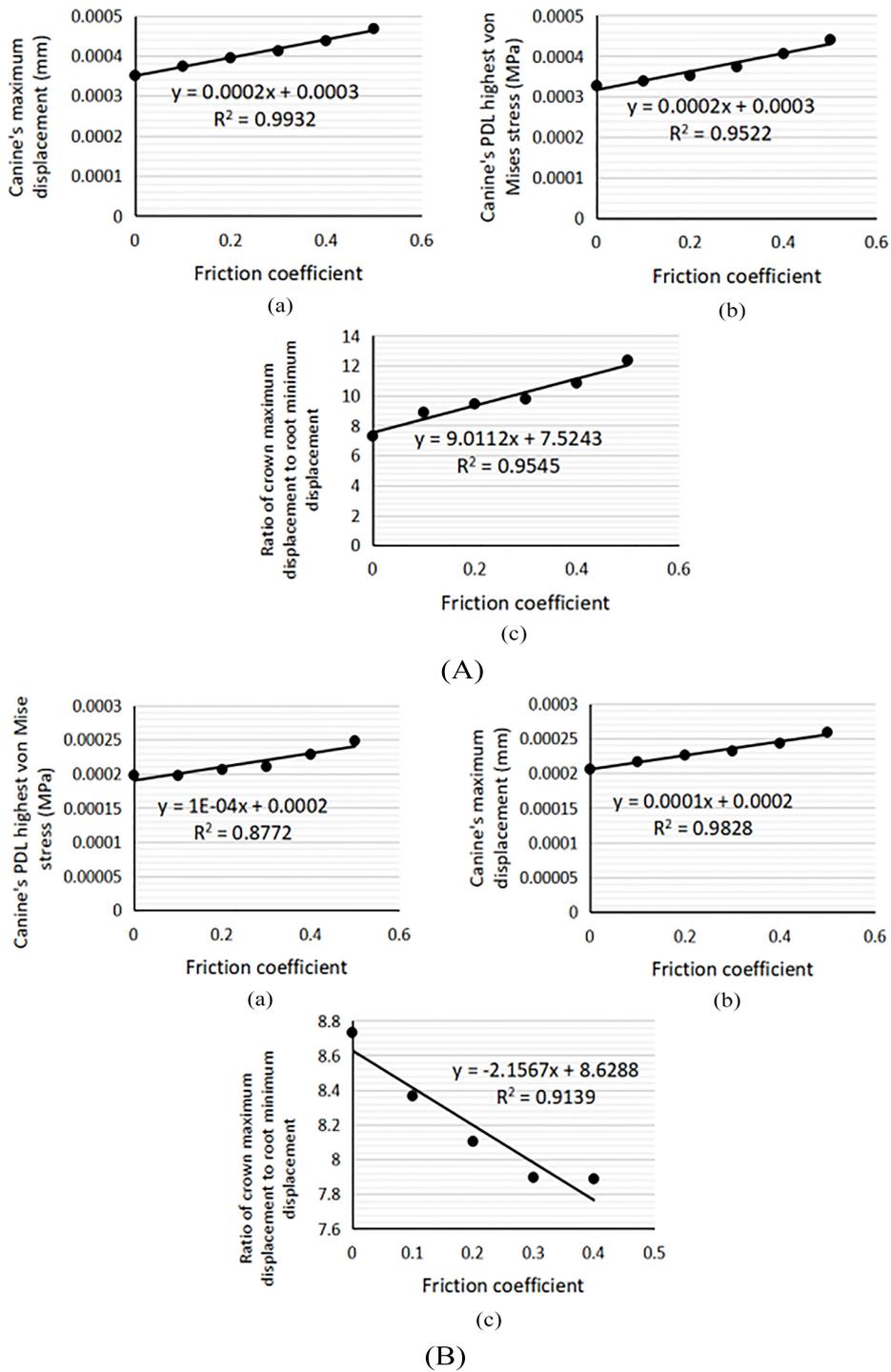
Fig. 3. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); Rcr (c); in translation cases with No.4 round (A) and No.9 rectangular (B) archwires.
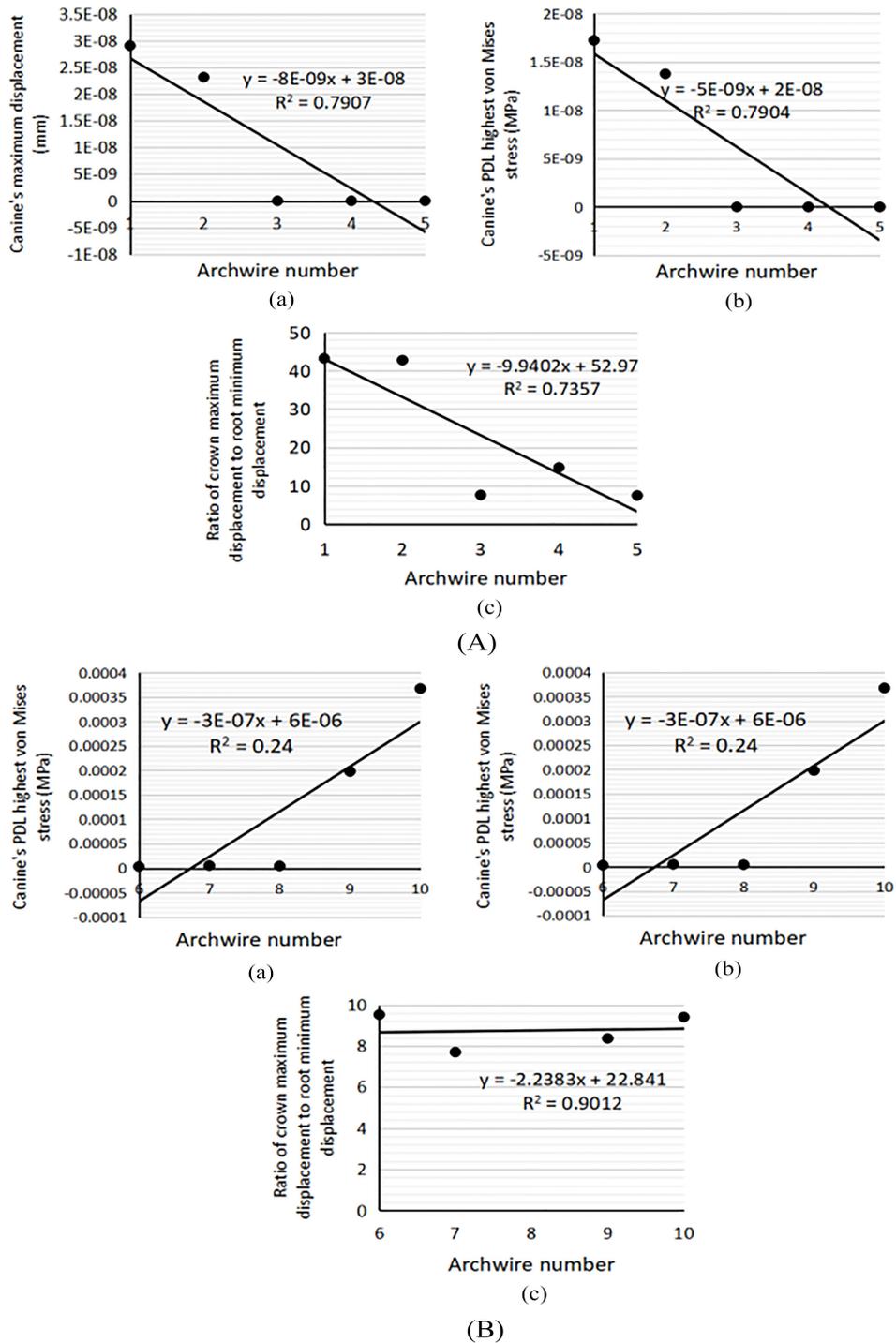
Fig. 4. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); Rcr (c); in rotation cases with the five round (A) and rectangular archwires (B) and 0.1 friction coefficient.
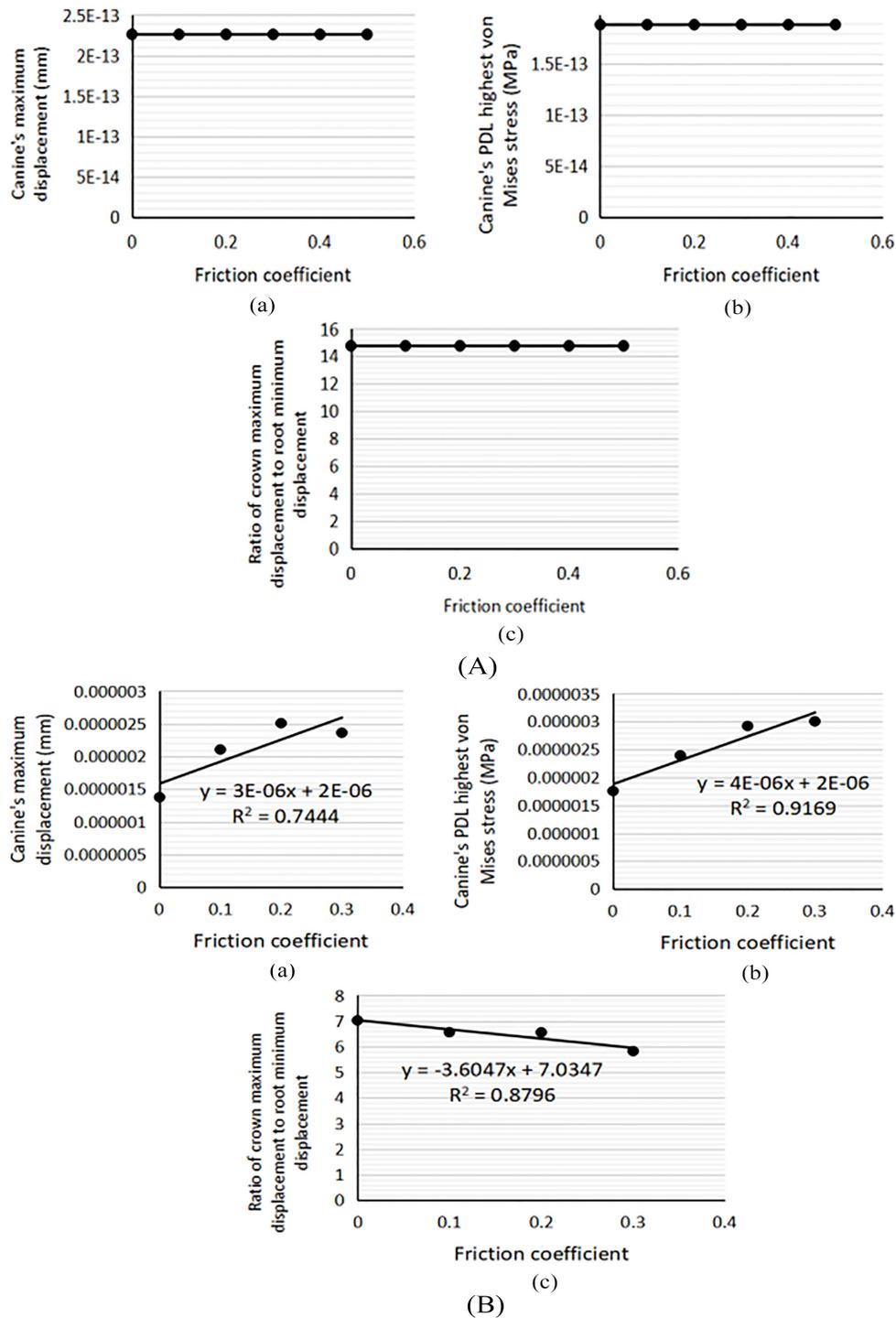
Fig. 5. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); Rcr (c); in rotate 2.5° cases with No.4 round (A) and No.9 rectangular (B) archwires.
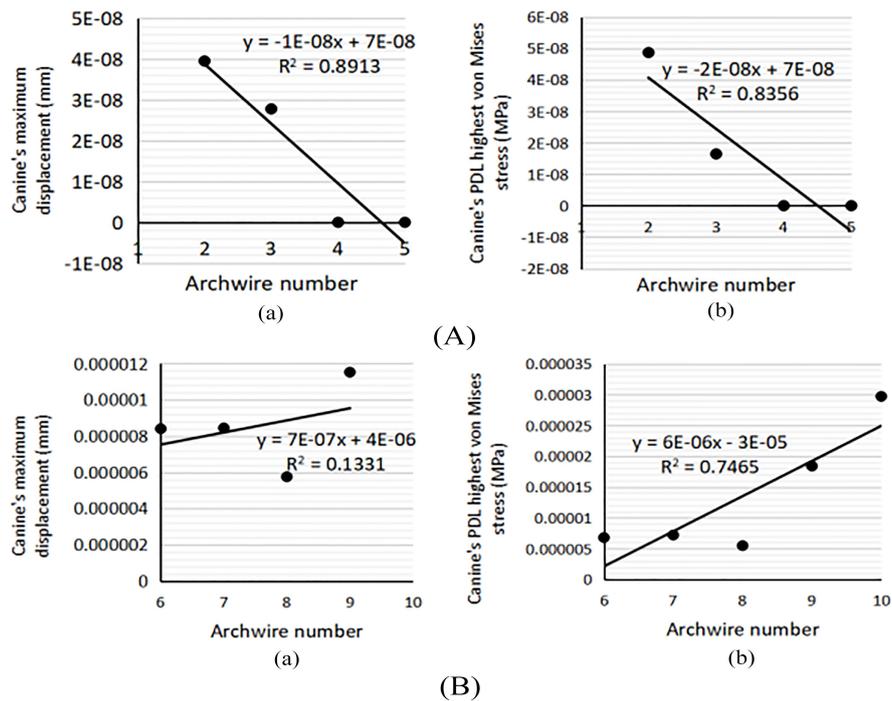
Fig. 6. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); in inclination cases with five round (A) and rectangular archwires (B) and 0.1 friction coefficient.

increase in the cross-section area in the rectangular archwire (Fig. 6B). In the round archwire cases, the assesed parameters remained nearly invariant during the different friction coefficients (Fig. 7A). In the rectangular archwire cases, the assesed parameters increased with an increase in the friction coefficient. However, the extent of the increase was minimum (Fig. 7B).

4. Discussion

Self-ligating orthodontic have presented an increased diffusion in the orthodontic practice in the past decades. It is urgent to understand its biomechanical characteristic clearly. Gómez et al. [12] found that the passive self-ligating brackets presented a less frictional resistance and greater contact area between the slot and the archwire, while the spring clip increased the frictional resistance than the conventional ligating treatment. Hence, we conducted this study to evaluate the canine displacement, the PDL stress, and the rotation center related changes in the canine on three types of tooth movement under various friction coefficients, wires with different cross-section shapes and sizes, and different archwire displacements.

Papageorgiou et al. [13] concluded that the archwire had the largest influence on the orthodontic tooth movement and stress in PDL. The results of this study were consistent with their conclusion. Furthermore, this study illustrated the specific influence trends in various movement styles.

Considering the translation movement, the larger the archwire cross-section area is, the quicker the canine translates. The friction between an archwire and bracket can improve the 3D control of the translation in the round archwire cases. However, an increase in the friction coefficient may cause PDL necrosis in the rectangular archwire cases.
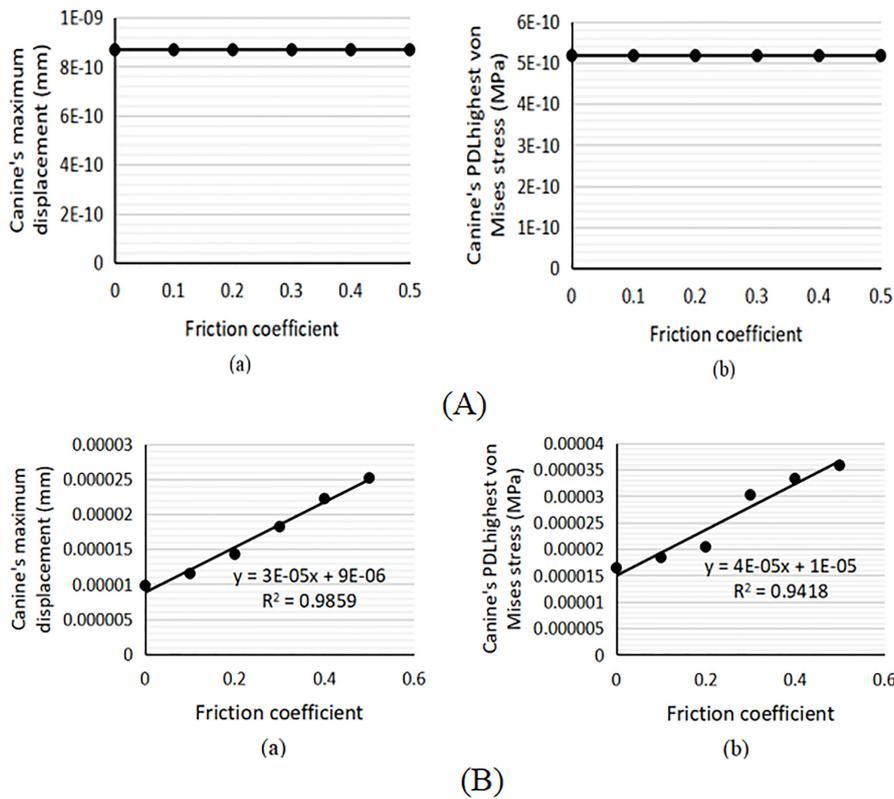
Fig. 7. Maximum canine displacement (a); highest PDL von Mises stress of the canine (b); in incline 3° cases with No.5 round (A) and No.9 rectangular (B) archwires.

Considering the rotation movement, a larger cross-section round archwire decreases rotation control of the canine. The friction coefficient has a minimal influence on the rotation movement of the canine in both the rectangular and round archwire cases.

Considering the inclination movement, a large cross-section area in a round archwire may limit the inclination movement of the canine. However, a large cross-section area rectangular archwire may improve the inclination of the canine. Low friction coefficient has no influence on the inclination of the canine in the round archwire cases, whereas a high friction coefficient may cause PDL necrosis in the rectangular archwire cases.

5. Conclusion

The results of the present investigation demonstrated that the archwire characteristics had the direct influence on the self-ligating orthodontic tooth movement of the canine. Our findings can provide a reference guide to the orthodontists for choosing the proper archwires for special tooth movement needs.

Acknowledgments

Conflict of interest

None to report.

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