The cross-sectional effects of ribbon arch wires on Class II malocclusion intermaxillary traction: A three-dimensional finite element analysis

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Research Article

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Abstract

Background: The application of intermaxillary traction is often accompanied by the unexpected movement of dentition, especially anchorage teeth. The aim of this study was to comprehensively compare the influence of cross-sectional shape of ribbon arch wires with edgewise and round wires on intermaxillary traction in Class II malocclusion treatment using FEA simulation.

Methods: The dentofacial structure was simulated in finite element software. A retraction force of 1.5 N was applied to different cross-sectional orthodontic arch wires: a ribbon wire (0.025×0.017-inch and 0.025×0.019-inch), a rectangular wire (0.017×0.025-inch and 0.019×0.025-inch) and a round wire (Φ 0.018-inch and Φ 0.020-inch).

Results: Among the three groups, ribbon wire (0.025×0.017-inch and 0.025×0.019-inch) exhibited the lowest displacement in the X-axis (12.61 μm and 12.77 μm, respectively) and Z-axis (8.99 μm and 9.06 μm, respectively). However, the 0.025×0.017-inch ribbon wire showed the highest Y-axis displacement. In the round wire group, Φ 0.020-inch wire displayed less rotation than Φ 0.018-inch wire, where the sagittal, frontal and occlusal rotation of Φ 0.020-inch wire was almost half of that of Φ 0.018-inch wire. The movement of the first molar region was intermediate between the ribbon arch group and the round wire group. Notably, the values of the 0.025×0.017-inch arch wire displacement, which were much higher than those of any other group, peaked at 0.019 mm in the central incisor region with a spike-like shape. The deformation range of the Φ 0.018-inch wire group was the largest in this study.

Conclusions: The cross-section of the arch wire influenced force delivery in Class II intermaxillary traction. With the same shape, a larger cross-sectional area would lead to less mandibular dentition movement. For the rectangular arch wire and ribbon arch wire groups, since the height and width were inverted, the vertical displacement of anchorage teeth in the ribbon wire group was significantly reduced, but the possibility of buccal tipping in mandibular anterior teeth also increased.

Background

Class II malocclusion, which is associated with a convex soft tissue profile caused by excessive growth of maxilla and/or mandibular retrognathism, constitutes a significant percentage of the patients seeking orthodontic treatment [1-4]. Among the various treatment modalities employed, intermaxillary traction generates a pulling force via ligatures and has been one of the most widely used techniques [5]. Intermaxillary traction should be used with caution, especially for those patients with high-angle Class II malocclusion, since this approach was frequently accompanied by anchorage loss, namely, unexpected movement of the permanent mandibular molar [6].

Previous studies have suggested the geometry and size effects of orthodontic arch wires on the ultimate orthodontic treatment outcomes [7, 8]. Brackets and arch wires were the main components of fixed appliance systems, in which the arch wire served as a means of originating and delivering force. Pandis et al. reported that the characteristics of wire were more pronounced than the ligating mechanism of brackets in force-deflection curves [9]. During orthodontic treatment, different cross-section arch wires were chosen and sequenced based on the periodical goal [10]. The initial phase was often conducted with undersized round cross-sectional arch wire to provide continuous lower forces and for fastening during the alignment process, whereas the larger edgewise arch wire was selected in the adjustment period to enhance torque effectiveness.

Compared with contemporary edgewise wires, the cross-section of ribbon arch wires was an inversion of height and width. Historically, the ribbon arch, the first orthodontic appliance coupled with brackets, was considered the progenitor of edgewise appliances and earned popularity in the 1920s [11]. The utility of the ribbon arch has been extinguished since the introduction of edgewise wire. Although attempts have been made to increase ribbon arch usage, especially in lingual treatment, very few papers have involved ribbon wires in general orthodontic applications [12].

In addition, there is a paucity of data from investigations into the role that the cross-sectional shape played in maxillomandibular traction. The reason for this lack of data could be the great challenge in identifying tooth movement and deformation under the coexistence of sophisticated anatomical structures and various orthodontic elements [13]. Finite element analysis (FEA), which is an engineering and mathematical method in reaction prediction, has been suggested to be a reliable method in orthodontic research through craniofacial complex remodelling [14-17].

The aim of this study was to comprehensively compare the influence of cross-sectional shape of ribbon arch wires with edgewise and round wires on intermaxillary traction in Class II malocclusion treatment using FEA simulation.

Methods

The study protocol was designed in compliance with the Helsinki declaration and approved by the ethical committee of the Fujian Medical University union hospital. Before inclusion in this study, an informed consent form was signed by a 20-year-old healthy male volunteer. The volunteer was selected through medical history interviewing and oral examination. The exclusion criteria were as follows: (1) History of endodontic, prosthodontic, or orthodontic therapy. (2) Non-treated periodontal diseases and/or caries. (3) Presence of active infection (pus, fistula). (4) Poor plaque control or lack of oral hygiene compliance. (5) Missing teeth; (6) Systemic diseases.

Finite element (FE) model was based on the computed tomography (Discovery CT750HD, GE, Boston, USA) data, which referred to the sectional images of the volunteer from the upper rim of the condyle to the lower edge of the mandible on digital imaging and communications in medicine (DICOM) format. The CT data was collected and imported to the processing software (Mimics 17.0, Materialise, Leuven, Belgium) to further obtain virtual model of the maxilla and mandible on Geomagic studio (Raindrop Geomagic, Morrisville, USA). Along with the outer surface of the mandible, the periodontal ligament (PDL) was constructed at 0.25 mm thickness. The central area of alveolar bone was cancellous bone surrounded by 1.5 mm thick cortical bone.

Rectangular wire (0.017×0.025-inch and 0.019×0.025-inch, 3M Unitek, Monrovia, USA), and round wire (Φ 0.018-inch and Φ 0.020-inch, 3M Unitek, Monrovia, USA) were scanned and these scans were entered into software (Unigraphics NX 8.5, Siemens PLM Software, Plano, USA). Using the same method, the matching brackets, buccal tubes and slots were modelled virtually. The ribbon wire (0.025×0.017-inch and 0.025×0.019-inch) was constructed based on the rectangular wire with height and width inverted. The rectangle wires and round wires were coupled with a 0.022×0.028-inch slot, whereas the ribbon wire was inserted into the 0.028×0.022-inch slot, which was designed for the purpose of fitting the upright arch wire. An anterior hook of 2.5 mm height was built and positioned between the maxilla lateral incisor and canine. In addition, stainless steel ligature wires were tied to the brackets from the second premolar of the mandible right to the left second premolar, where the relative sliding friction was allowed between the ligature and brackets and the friction coefficient was 0.2. The tubes were placed in the first mandible premolar and second premolar, and the friction coefficient between the tubes and arch wire was also 0.2. Those orthodontic appliances were assembled appropriately on the buccal side of dentition and are shown in Figure 1.

FE analysis was performed and visualized using Ansys Workbench 15.0 (Ansys Inc., Canonsburg, USA). Each anatomical component and orthodontic appliance was simulated in tetrahedral elements and assumed isotropic homogenous linear elastic characteristics. Young's modulus and Poisson's ratio of cortical bone, cancellous bone, teeth, PDL, arch wires, brackets and tubes were determined from a previous study [18] and are shown in Table 1.

A traction force of 1.5 N was applied from the maxilla anterior hook between the canine and lateral incisor to the hook of buccal tubes in the mandible first molar. The application of retraction force would initiate the movement of teeth, which could be denoted as the displacement rotation of teeth, and the stress redistribution of PDL. The displacement of teeth was recorded on the basis of a coordinate system with the x-axis as the anterior-posterior direction, the y-axis as the medial-lateral direction, and the z-axis as the superior–inferior direction, whereas the anterior, medial, and superior directions were defined as the +x, +y, and +z directions, respectively. Rotation movement was decomposed into three planes of motion (sagittal, frontal and occlusal), and the corresponding directions (posterior, medial and mesial, respectively) were predetermined as positive. The buccal cusps of the mandibular posterior teeth and the edge of anterior teeth were lined virtually as buccal lines, while the lingual cusps of mandibular posterior teeth and the cingulum of anterior teeth were connected as lingual lines. The movement of the lingual line and buccal line was recorded.

Results

Movement of anchorage teeth

The results of 46 teeth in terms of force component distribution, displacement and rotation movements in three directions were shown in Table 2. Regarding the force distribution of 46 teeth, very similar results were found for the 0.017×0.025-inch and 0.019×0.025-inch wires. The force components of the X-axis, Y-axis and Z-axis were approximately 1.36 N, 0.31 N and 0.45 N, respectively. Compared with the rectangular wire and round wire groups, the ribbon wire group had the lowest force component in three directions, and the force of the 0.025×0.017-inch group in the X-axis, Y-axis and Z-axis was 1.31 N, 0.29 N, 0.43 N, respectively. The round wire group displayed the highest X-axis force and Z-axis force (1.39 N and 0.48 N, respectively).

For the rectangular wire group, with increasing wire size, there was a descending trend of the displacement in the Y-axis and Z-axis. The displacement of the 0.017×0.025-inch wire in the Z-axis direction was 9.17 μm and that of the 0.019×0.025-inch wire was 9.13 μm. Among the three groups, ribbon wire (0.025×0.017-inch and 0.025×0.019-inch) exhibited the lowest displacement in the X-axis (12.61 μm and 12.77 μm, respectively) and Z-axis (8.99 μm and 9.06 μm, respectively). However, the 0.025×0.017-inch ribbon wire showed the highest Y-axis displacement. The Φ 0.018-inch round wire also showed higher Z-axis displacement (9.44 μm) and Y-axis displacement (5.96 μm) than Φ 0.020-inch round wire (9.20 μm and 4.40 μm, respectively).

In the rectangular wire group and ribbon wire group, the rotation motion for 46 teeth in the sagittal, frontal and occlusal planes was -0.002°, 0.020°, and 0.021°, respectively. In the ribbon wire group, the frontal rotation was much higher than that in the rectangular and round wire groups, especially the 0.025×0.017-inch group, which exhibited 0.042° of rotation. In the round wire group, Φ 0.020-inch wire displayed less rotation than Φ 0.018-inch wire, where the sagittal, frontal and occlusal rotation of Φ 0.020-inch wire was almost half of that of Φ 0.018-inch wire.

Von-Mises stress distribution of the mandibular PDL

Figure 2 illustrates the buccal view and occlusal view of the PDL Von-Mises stress distribution. In the posterior zone, the PDL of the first molar endured the most stress, especially in the distal root, and stress decreased gradually in the mesial direction. In the anterior zone, there was an increasing trend of stress from the canine tooth towards the central incisor. As shown in Figure 2, there was a very slight difference caused by the cross-sectional area in the PDL stress distribution, and the maximum stress was approximately 0.01 MPa.

Deformation of mandible dentition

The detailed movement (X-axis, Y-axis and Z-axis) of mandible teeth after the application of 1.5 N retraction force is shown in Figure 3. In the X-axis direction, all the teeth were inclined mesially due to the retracting force. As the cross-sectional area enlarged, the deformation of the X-axis was reduced in all groups. In the Y-axis direction, the posterior teeth were tipped to the lingual side, whereas the anterior teeth exhibited a labial-oriented motion. In the Z-axis direction, the first molar moved in an upward direction, but the central incisor had an opposite trend, indicating that the anterior teeth might intrude vertically since the posterior teeth tilted inward. The largest vertical deformation among mandible dentition was exhibited in the mandibular first molar, where the ribbon wire group exhibited the least vertical movement and the round wire group showed the highest deformation.

Deformation of the buccal line and lingual line

The displacements of the buccal line and lingual line are shown in Figure 4 (red refers to the buccal line, and blue refers to the lingual line). From the observation of the curve contour, the tendency of the buccal line and lingual line in different arch wire groups showed some similarity. The displacement was dramatically increased in the first molar region, followed by a slight decrease in the premolar zone before subsequently rising in the anterior teeth region.

In the rectangular wire group (0.017×0.025-inch and 0.019×0.025-inch), the maximum displacements of the buccal line and lingual line were approximately 0.016 mm and 0.014 mm, respectively. The movement of the first molar region was intermediate between the ribbon arch group and the round wire group. In the ribbon arch group, the lingual line deformation in the first molar region was approximately 0.008 mm, and it was also the lowest among the corresponding results of all the studied groups. Notably, the values of the 0.025×0.017-inch arch wire displacement, which were much higher than those of any other group, peaked at 0.019 mm in the central incisor region with a spike-like shape. In the 0.025×0.019-inch group, the displacements ranged from the first molar to the central incisor of the buccal line, and the lingual line was lowest among the studied groups. In the round wire group, the displacement ranges from the first molar to the central incisor of the buccal line and lingual line were higher than those of the rectangular and ribbon arch groups. The movement induced by the Φ 0.020-inch wire was approximately 0.0165 mm, which was lower than that induced by the Φ 0.018-inch wire.

Deformation of arch wire

Arch wire deformation is summarized in Figure 5. The rectangular wire group and ribbon wire group displayed a relative stress concentration in the anterior zone. The deformation range of the Φ 0.018-inch wire group was the largest in this study. The deformation range was almost the same in the rectangular wire group with different sizes, and the deformation value was approximately 0.007 mm.

Discussion

The high prevalence of Class II malocclusion in patients prompted the wide usage of intermaxillary elastic traction. However, scarce data and few documented details are available regarding the influence of arch wire geometry during the maxillomandibular traction procedure. In the present study, we principally aimed to simulate the dentofacial structure via FEA to explore the effect of arch wire cross-sectional shape on Class II intermaxillary traction.

Often, the changes in vertical and horizontal vectors caused by Class II intermaxillary traction are concerned with anchorage loss [6, 19, 20]. There was an average growth of 5.0 mm of the lower face height after an average duration of 1.3 years for the fixed appliances and Class II elastics, with which mandibular growth could surpass maxilla growth by 1.1 mm [4]. Since maxillary growth was suppressed by intermaxillary traction, Jason et al. observed a 1.2 mm mesial movement of the mandibular first molar [5]. Nina el al. found that there was an open bite in half of the high-angle Class II patients who received bimaxillary surgery and mandibular skeletal relapse in 40% of the patients [21]. The adverse effect of anchorage loss would bring about clockwise rotation of the occlusal plane and aggravate the treatment difficulty of high-angle Class II malocclusion.

Based on the FEA model in this study, differential results were observed in the arch wire group with different cross-sections in terms of mandibular first molar movement. Mechanics of arch wire have been recognized as one of the contributing factors of anchorage loss but have not been fully investigated [5]. Theoretically, the moment of inertia (*I*) of the rectangular wire is equal to "$h^3w/12$" (where "h" refers to the height of the cross-section and "w" refers to the width); the *I* of the round wire is equal to "$\pi r^4/64$" (where "r" refers to the radius of the cross-section) [10]. When the diameter of the circular wire is enlarged by 20%, the bending stiffness is almost doubled [22]. In addition, the magnitude of the height in the cross-section of the rectangular wire was far greater than the width. The formula indicated the possibility of creating a more rigid rectangular wire by only changing the height and without changing the total area. In this study, the ribbon wire group exhibited the lowest vertical and horizontal displacement, followed by the rectangular wire group and round wire group.

In this FE study, the remarkable execution of the ribbon wire in minimizing the vertical and horizontal displacements provided the basis for reviving the ribbon wire. The good performance of the ribbon wire in anchorage control could be attributed to the relatively greater height of the arch wire cross-section. The greater height would enlarge the moment of inertia and provide more rigid support to the occlusal plane. To our knowledge, only Inami et al. reported a minimum vertical bowing effect with a ribbon-wise lingual appliance [23]. However, they also pointed to insufficient control of the ribbon wire in lingual tipping due to the thinner geometry, and the palatal bar was needed to keep the tooth upright. The drawback was consistent with the FEA results in this study since the ribbon wire group displayed greater Y-axis displacement and frontal rotation.

The intermaxillary retraction force was not only applied to teeth but was also transmitted to the surrounding tissue, such as the PDL. By observing the stress distribution of the PDL, the possibility of root resorption could be obtained. There were very similar results displayed by different arch wire groups in which the distal root endured the most stress. Previous studies also admitted the relatively high occurrence of root resorption in the distal root of the mandibular first molar in orthodontic treatment [24]. The very similar results of the Von-Mises stress distribution among the rectangular wire, ribbon wire and round wire groups indicated PDL insensitivity to the cross-section of the arch wire. However, the results should be carefully interpreted since the PDL was characterized as an isotropic homogenous linear elastic ligament in this FE study.

The displacement results of the buccal line and lingual line as well as the deformation of mandibular dentition also demonstrated that there was an association between cross-sectional geometry and mandibular tooth movement in Class II intermaxillary traction. Monlasser et al. stated that the importance of the arch wire cross-section in mechano-therapy should be appreciated since the force level in the vertical direction would be amplified from 16% to 120% when the 0.014-inch arch was replaced by the

0.016-inch [25]. In this study, with the same shape, a larger cross-sectional size would result in mandibular dentition movement. The increasing interspace between the bracket and arch wire induced less friction and less slack in the root controls, which might be detrimental to the en masse retraction of maxillary anterior teeth [26]. Similarly, the displacement ranges from the first molar to the central incisor of the buccal line and lingual line were higher than those of the rectangular and ribbon arch groups.

Arch deformation was directly correlated with the resistance to sliding, and permanent wire deformation would heavily encumber tooth movement efficiency [27]. From the perspective of the second moment of inertia, the ribbon arch wire group (0.025×0.017-inch and 0.025×0.019-inch) had greater bending resistance than that of the rectangular wire group (0.017×0.025-inch and 0.019×0.025-inch) since the width and height were inverted. Compared with that of the rectangular wire group, the vertical displacement of anchorage teeth in the ribbon wire group was significantly reduced, but the possibility of buccal tipping of mandibular anterior teeth was also increased. The 0.025×0.017-inch ribbon arch wire group showed a spike-like shape peak in the central incisor area, indicating inferior control of the mandibular anterior region, as mentioned previously. Studies have concluded that round arch wires generate lower friction than rectangular wires [28, 29]. However, in this study, the round arch wire, especially the Φ 0.018-inch wire, displayed greater arch deformation than the edgewise groups. The reason might be ascribed to the relatively lower bending stiffness of the round arch wires. The wire deformation of the rectangular arch was close to that of the ribbon arch group.

There were some limitations in this study because this experiment was conducted entirely using computer software. For instance, the setting of biological characteristics may differ from the real properties in vivo. Future studies, especially clinical trials, should be conducted to investigate the effect of arch wire geometry in vivo.

Conclusions

Within the limitations of this FEA, the cross-section of the arch wire exerted an influence on force delivery in Class II intermaxillary traction. With the same shape, a larger cross-sectional size led to smaller mandibular dentition movement. For the rectangular arch wire and ribbon arch wire groups, since the height and width were inverted, the vertical displacement of anchorage teeth in the ribbon wire group was significantly reduced, but the possibility of buccal tipping of mandibular anterior teeth also increased.

Declarations

Ethics approval and consent to participate

The study protocol was designed in compliance with the Helsinki declaration and approved by the ethical committee of the Fujian Medical University union hospital. Before inclusion in this study, an informed consent form was signed by a 20-year-old healthy male volunteer.

Consent for publication

Not applicable

Availability of data and material

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

DL was responsible for finite element simulation and project designing. QX was involved in literature reviewing, writing paper and data interpretation. All authors read and approved the final manuscript.

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Tables

Table 1: Elasticity properties of materials in this study

	Poisson's ratio	Young's modulus (MPa)
Cortical bone	0.26	13700
Cancellous bone	0.30	1370
Teeth	0.30	19600
PDL	0.45	0.667
Tubes, brackets	0.30	206000
Arch wire	0.30	176000

Table 2: The results of 46 teeth in terms of force component distribution, displacement and rotation movements in three directions

Group	Size	Force(N)			Displacement (μm)			Rotation(°)		
		X-axis	Y-axis	Z-axis	ΔX	ΔY	ΔZ	Sagittal	Frontal	Occlusal
Rectangular wire	0.017×0.025-inch	1.36	0.31	0.46	13.44	4.63	9.17	-0.002	0.020	0.021
	0.019×0.025-inch	1.36	0.31	0.45	13.45	4.58	9.13	-0.002	0.020	0.020
Ribbon wire	0.025×0.017-inch	1.31	0.29	0.43	12.61	6.50	8.99	-0.003	0.042	0.045
	0.025×0.019-inch	1.31	0.30	0.42	12.77	4.95	9.06	-0.003	0.025	0.026
Round wire	Φ 0.018-inch	1.39	0.29	0.48	13.76	5.96	9.44	-0.002	0.034	0.036
	Φ 0.020-inch	1.39	0.29	0.48	13.81	4.40	9.20	-0.001	0.016	0.017

Figures

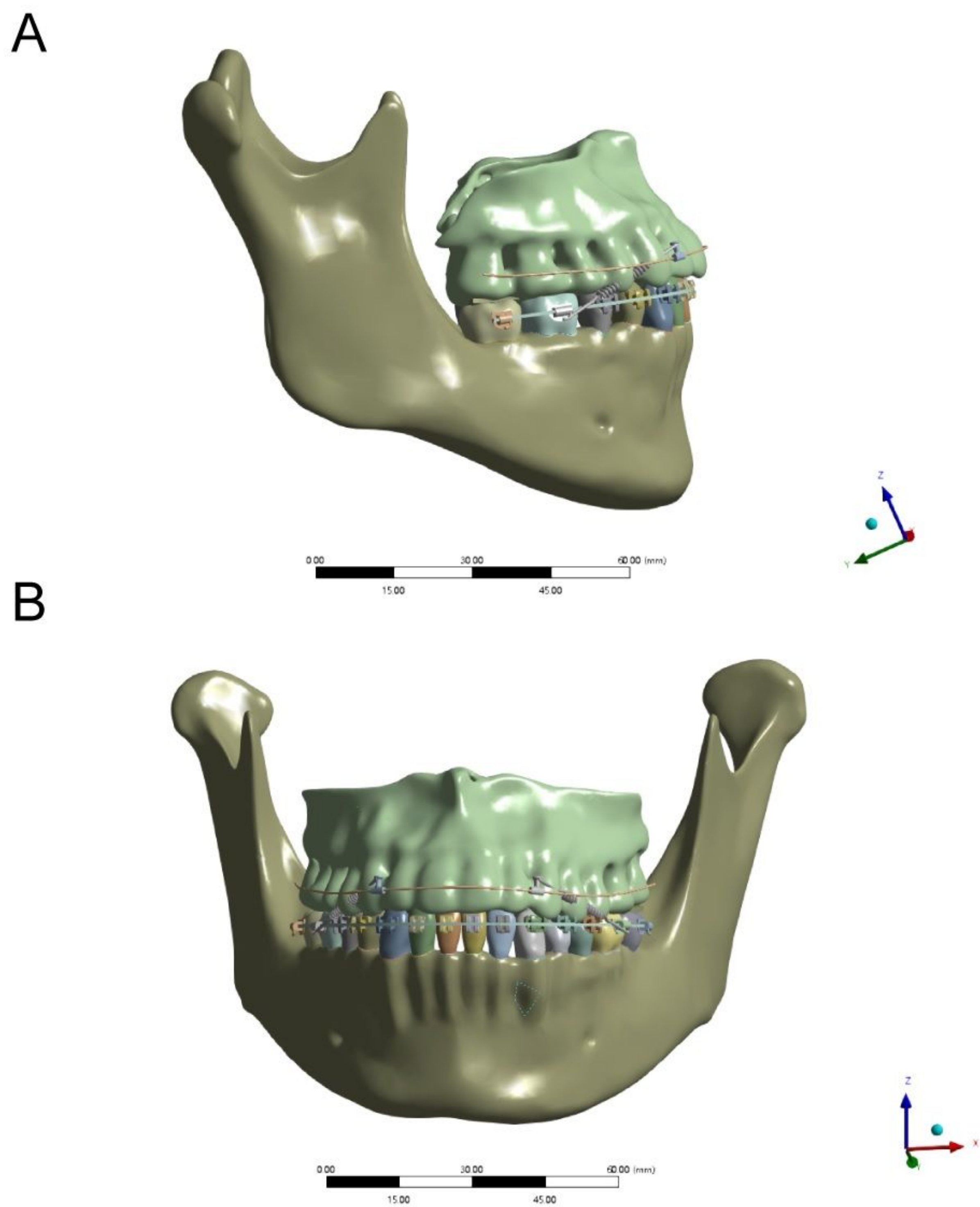

Figure 1

Dento-craniofacial simulation in the FEA with retraction force (A:side view; B:frontal view)

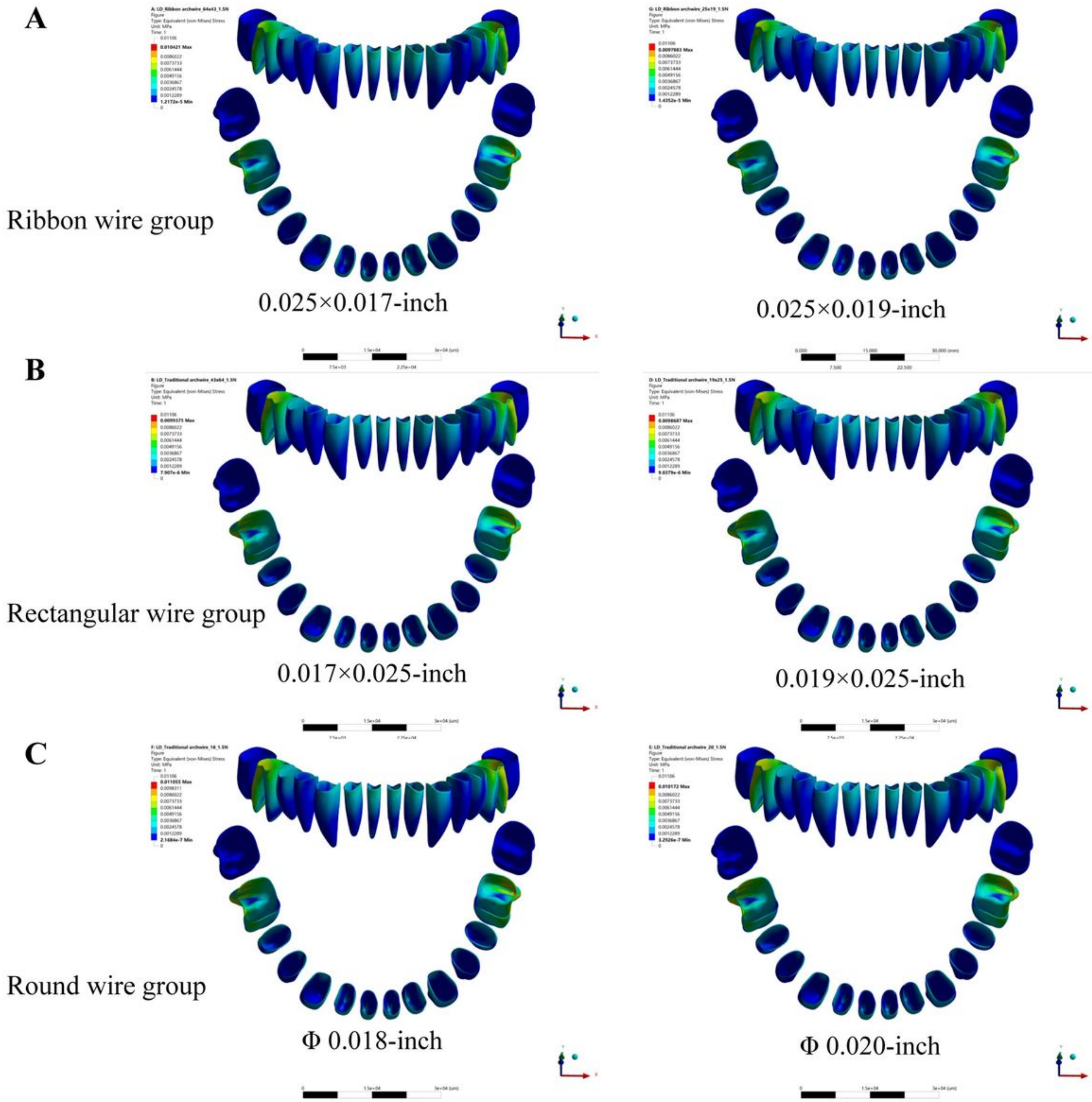

Figure 2

The buccal view and occlusal view of the PDL Von-Mises stress distribution. (A: Ribbon arch wires; B: Rectangle arch wires; C: Round arch wires)

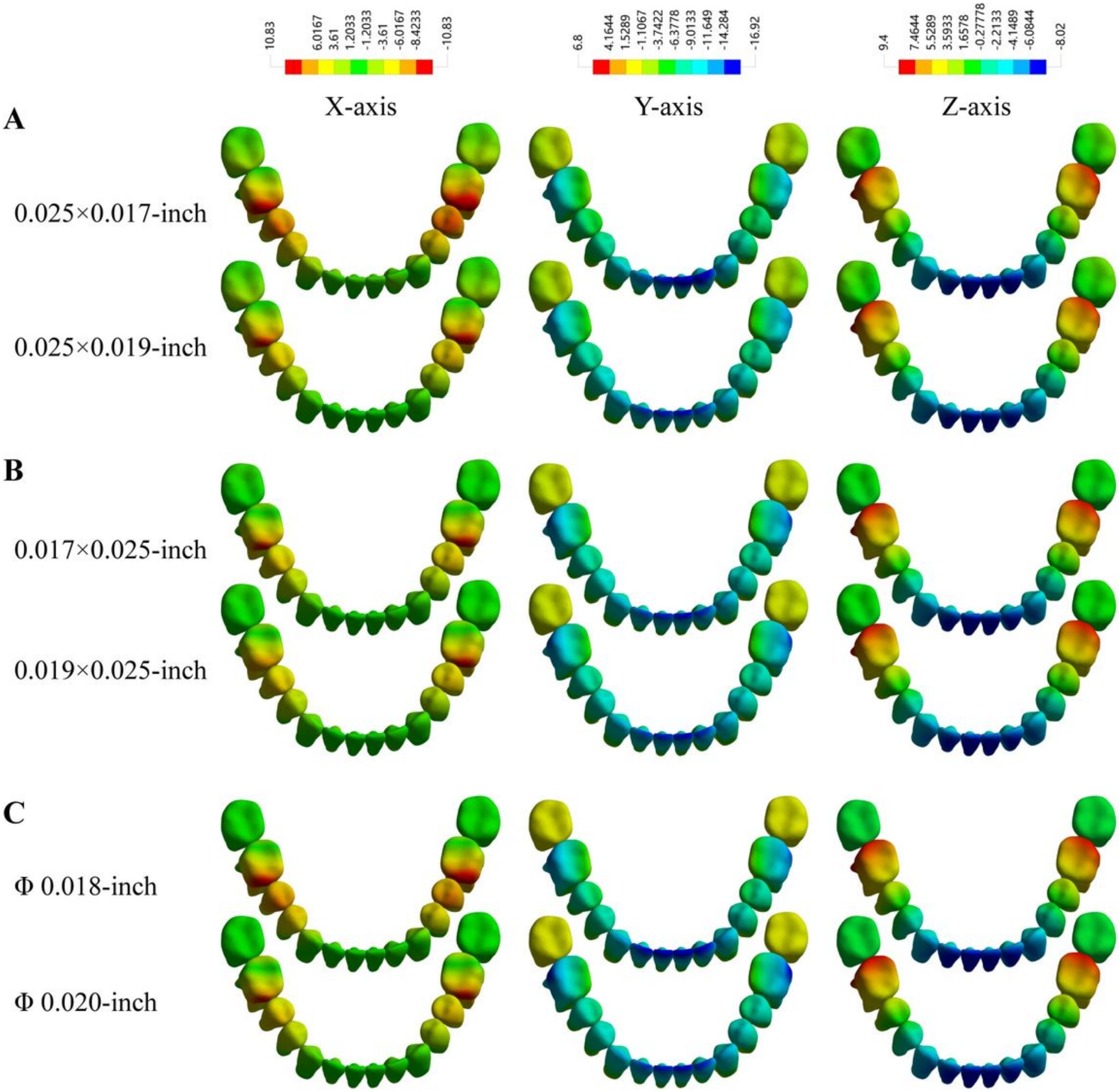

Figure 3

Deformation of the mandible dentition (A: Ribbon arch wires; B: Rectangle arch wires; C: Round arch wires)

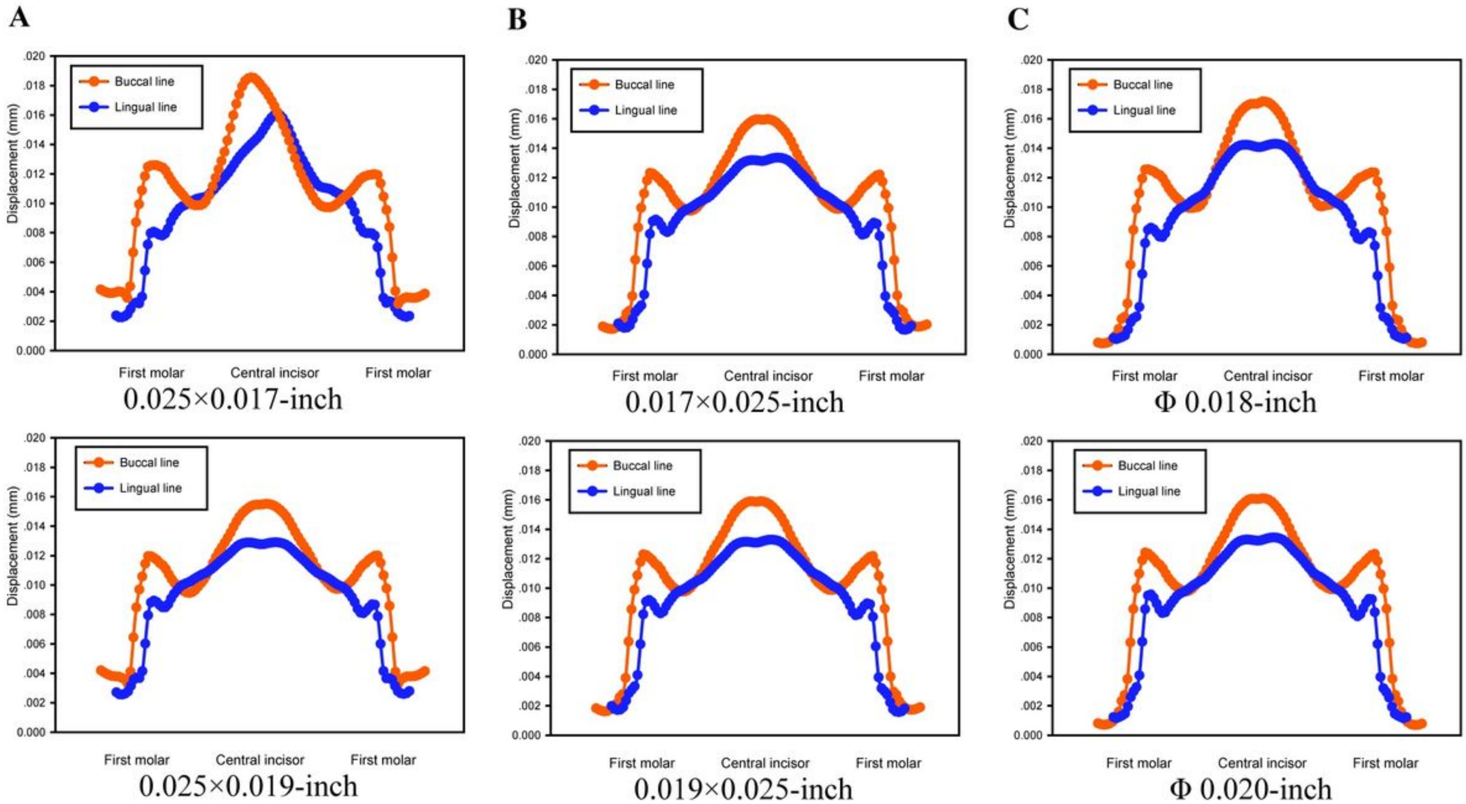

Figure 4

The buccal line and lingual line displacement (A: Ribbon arch wires; B: Rectangle arch wires; C: Round arch wires)

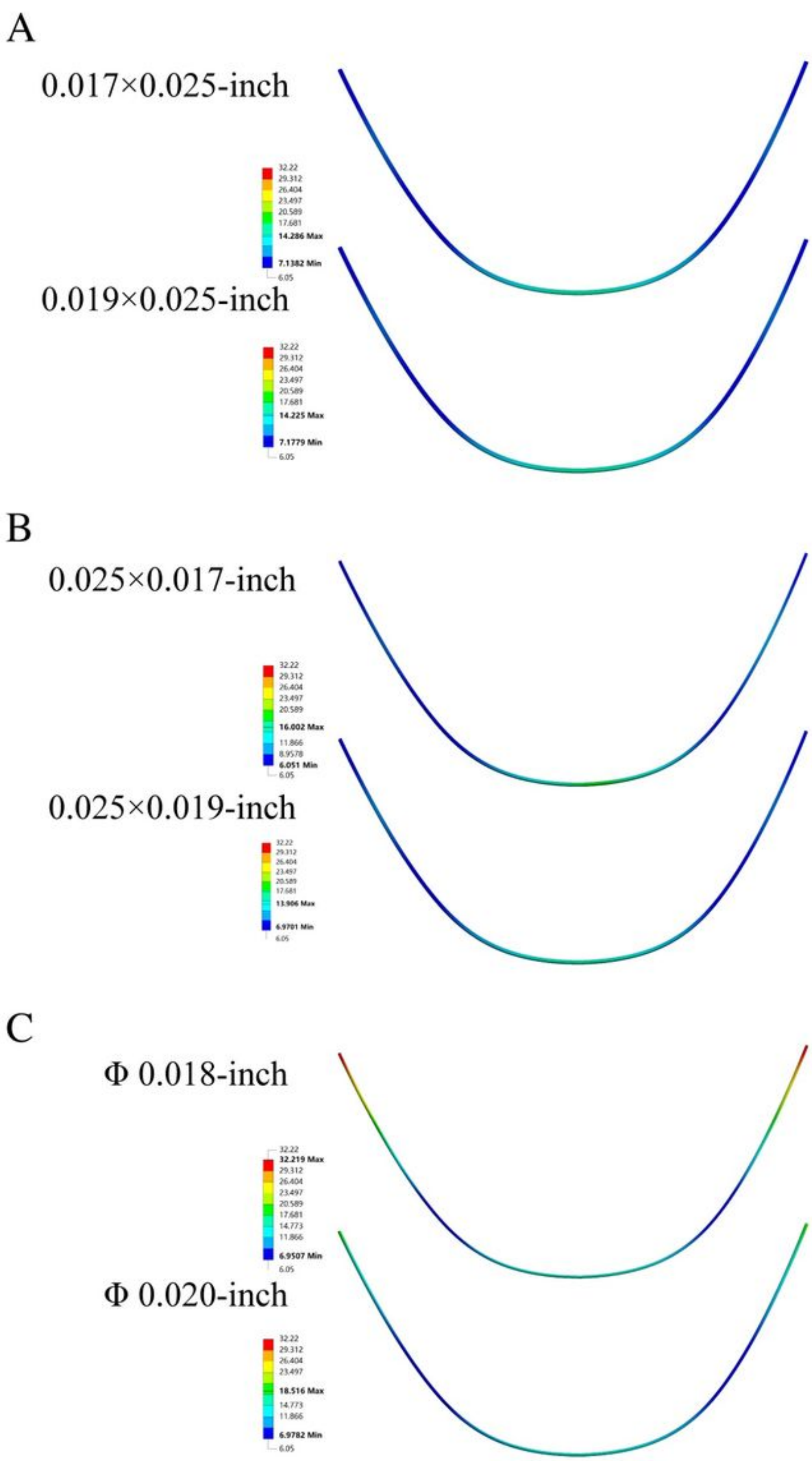

Figure 5

Arch wire deformation of the rectangular arch wire, ribbon arch wire and round arch wire groups (A: Ribbon arch wires; B: Rectangle arch wires; C: Round arch wires)