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Optimum En-Masse Retraction of Six Maxillary Anterior Teeth in Lingual Orthodontics: a Numerical Investigation with 3-Dimensional Finite Element Analysis

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Abstract: The objective of this study was to devise an optimum force system to achieve en-masse retraction of six maxillary anterior teeth in lingual orthodontics (LiO). First, the set of equations was developed based on the mathematical computation to estimate optimum parameters of force system. Then, the computer software based on this mathematical computation was developed for the ease of estimation of force system. The verification of force system obtained with computer software was accomplished by three-dimensional finite element analysis (FEA). In FEA, it was clear that the desired en-masse retraction of six maxillary anterior teeth in LiO was achieved as observed from the vectors of nodal displacements as well as positions of undeformed and deformed models. In this way, mathematically computed optimum force system was verified with FEA. For orthodontists, the developed computer software accurately estimates the required force system according to mathematical computation. It simplifies the task of computation for orthodontists. The orthodontists can easily operate this computer software as it is user-friendly. Further, in-vivo validation of this study is required in future before clinical application.

Keywords: En-masse retraction, six maxillary anterior teeth, LiO (lingual orthodontics), mathematical computation, computer software, FEA (finite element analysis).

1 Introduction

In orthodontic treatment, the applied external force system maintains the occlusion of teeth by rearrangement to a desirable position [Song, Huh and Park (2004)]. The demand of lingual orthodontic treatment has now increased in adults due to aesthetics purpose. Dental protrusion is a common problem in orthodontic patients. In this dental problem, protrusion

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of lips and face convexity is observed which develops owing to dento-alevolar flaring of maxillary or both maxillary and mandibular anterior teeth. In the treatment of dental protrusion, first all the pre-molar teeth are extracted and then en-masse retraction of anterior teeth is achieved [Upadhyay, Yadav and Patil (2008)].

The best orthodontic treatment estimates and controls the movement of teeth without any damage to surrounding tissue structures. Hence, biomechanical analysis of devised orthodontic force system is advised before its clinical application. The biomechanical analysis is a key method to predict and optimize teeth movement [Kim, Suh and Kim et al. (2010)].

Previous researchers have used different methods i.e. photo-elasticity [Brodsky, Caputo and Furstman (1975)], laser holography [Burstone and Pryputniewicz (1980)] and finite element analysis (FEA) [Kim, Suh and Kim et al. (2010); Shroff, Yoon and Lindauer et al. (1997); Park, Choi and Choi et al. (2007); Sung, Jang and Chun et al.(2010); Chetan, Keluskar and Vasisht et al. (2014); Uddanwadiker (2013)] to verify the pattern of orthodontic teeth movement. Among all of them, FEA was considered to be the best suitable method for biomechanical analysis. In FEA, accurate computer modelling of teeth anatomy is quite possible [Kim, Suh and Kim et al. (2010)].

Previous studies stated various treatment criteria to achieve en-masseretraction of six maxillary anterior teeth. These studies obtained the FEA results only Kim, Suh and Kim et al. (2010); Shroff, Yoon and Lindauer et al. (1997); Park, Choi and Choi et al. (2007); Sung, Jang and Chun et al.(2010); Chetan, Keluskar and Vasisht et al. (2014)]. However, only FEA results may mislead the orthodontist due to flaws in computer aided geometrical modeling and biomechanical analysis. The mathematical computation can accurately devise an optimum force system. While, FEA can be used to verify this mathematically computed orthodontic force system [Thote, Uddanwadiker and Sharma et al. (2016); Thote, Sharma and Uddanwadiker et al. (2017)].

Unlike labial orthodontics (LaO), lingual orthodontics (LiO) is an emerging and demanding field in orthodontics nowadays as it provides good aesthetics. LiO differs from LaO biomechanically. LiO, besides solving aesthetic needs, has a biomechanical advantage so far as the force application point (P_f) in relation to center of resistance (C_{res}) is concerned. As P_f is nearer to C_{res} in LiO, lesser torque or moment is required in LiO than in LaO to achieve certain type of tooth movement. This keeps the required force system within biological limit [Thote, Uddanwadiker and Sharma et al. (2016); Thote, Sharma and Uddanwadiker et al. (2017)].

The aim of this study was to achieve en-masse retraction of six maxillary anterior teeth in LiO. For the ease of estimation of required force system, computer software was developed for orthodontists based on the mathematical computation. To verify the computer software, three-dimensional FEA was performed and results of six maxillary anterior teeth movement were obtained in terms of vectors of nodal displacements along with undeformed and deformed models.

2 Materials and Methods

The retraction movement of teeth is movement in lingual direction. The retractive force on anterior teeth is generally applied at certain angle ϴ with respect to occlusal plane (OP). So, some amount of intrusive component is also present along with retractive component. If $\Theta = 0^\circ$, then retactive force is applied parallel to OP to achieve pure retraction (parallel translation). Fig. 1 shows the direction arrow representing retractive force vector of six maxillary anterior teeth. In Fig. 1, the four small perpendicular arrows represent different directions, i.e. labial, lingual, apical and occlusal as viewed from the distal aspect of a right maxillary central incisor.

Figure 1: Direction arrow representing retractive force vector of six maxillary anterior teeth as viewed from the distal aspect of a right maxillary central incisor.

Fig. 2 shows the required optimum force system for the en-masse retraction as viewed from the distal aspect of a right maxillary central incisor (all points were considered to be projected on sagittal plane). The arrow passing through force application point (P_f) represents the direction of teeth movement. Hence, this arrow also represents retractive force vector. Several points were considered in this study i.e. I = incisal edge of a maxillary central incisor, C_{res} = center of resistance of six maxillary anterior teeth, P_f = force application point on anterior teeth, P_a = posterior teeth anchorage point, T = point joining retractive force vector to perpendicular line through C_{res}. Occlusal plane (OP) was considered to be passing through point 'I'. The perpendicular distance between retractive force vector and C_{res} of six maxillary anterior teeth was considered as 'd'.

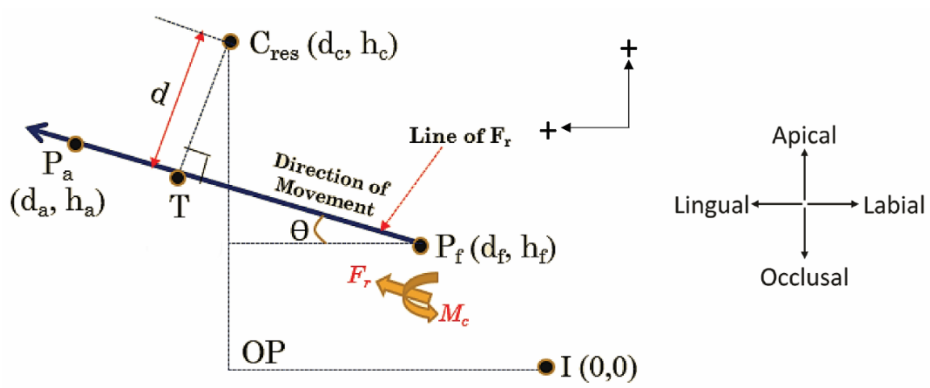

Figure 2: Optimum force system for en-masse retraction of six maxillary anterior teeth.

In Fig. 2, point I was considered as origin of a co-ordinate system i.e. I (0,0). In two-dimensional co-ordinate system, the lingual (horizontal) and apical (vertical) distances from point I were considered to be positive (represented by '+' symbol) in Fig. 2. To represent position of any point, the lingual and apical distance from point I were considered to be x and y co-ordinate respectively. The nomenclature of lingual and apical distance of different points with respect to incisal edge (point I) is reported in Table 1.

Table 1: Nomenclature of lingual and apical distance of different points with respect to incisal edge

No.	Points	Lingual distance in mm (x co-ordinate)	Apical distance in mm (y co-ordinate)	Co-ordinates of points (x, y)
[1]	P_f	d_f	h_f	(d_f, h_f)
[2]	P_a	d_a	h_a	(d_a, h_a)
[3]	C_{res}	d_c	h_c	(d_c, h_c)

Fig. 2 represents the optimum force system for the movement of retraction. The required direction of teeth movement (direction of retractive force vector) is inclined to occlusal plane (OP) by a certain angle represented by 'Θ'. The angle Θ is actually angle made by retractive force (F_r) vector (acting between points P_f and P_a) with respect to OP. In some cases, F_r force vector is horizontal and parallel to OP ($\Theta = 0^\circ$). While in other cases, it can be inclined to OP ($\Theta > 0^\circ$). But, this F_r force vector may be offset from C_{res} by a certain distance (d) which depends upon the positions of P_f, C_{res} and P_a. So, the resultant force system at C_{res} will be retractive force (F_r) and moment (M_f) developed due to F_r. This undesirable moment M_f will lead to uncontrolled crown tipping of teeth. Hence, to nullify the developed moment (M_f), a counteracting moment (M_c) should be applied at force application point (P_f) with equal magnitude and opposite direction as that of M_f in addition to F_r. Then, the resultant force system at C_{res} will be only a single retractive force (F_r). Thus, the required optimum force system at P_f to achieve en-masse retraction movement is a proper combination of retractive force (F_r) and a counteracting moment (M_c).

In this study, magnitude of applied retractive force (F_r) in grams was considered to be known to orthodontist which can be measured clinically. The position of C_{res} of six maxillary anterior teeth (d_c, h_c) was also considered to be known to orthodontist. Additionally, the positions of force application point on anterior teeth i.e. $P_f(d_f, h_f)$ and posterior teeth anchorage point i.e. $P_a(d_a, h_a)$ were considered to be known parameters and can be measured clinically. All these parameters were considered to be input parameters. So, the remaining parameter i.e. counteracting moment (M_c) in gram-force mm (gf.mm) was considered to be variable (unknown parameter). To estimate the optimum value ofM_c mathematically from all the other aforementioned input parameters, set of equations was developed.

2.1 Set of equations

The position of force application point (P_f) is labial and occlusal to C_{res} of six maxillary anterior teeth if the force is applied on them as shown in Fig. 2. The application of force at other positions of P_f (lingual or apical to C_{res}) is not preferred generally. Hence, in this study, set of equations was developed applicable for the position of P_f labial to C_{res}($d_f < d_c$) and occlusal to C_{res}($h_f < h_c$).

Some of the angles defined in set of equations (Fig. 3) are described as follows:

Θ = angle of retractive force (F_r) or line P_f-P_a with respect to occlusal plane (OP), Θ_t = angle between line joining force application point (P_f) and C_{res} (line P_f -C_{res}) with respect to OP, α = angle between F_r and line P_f -C_{res}.

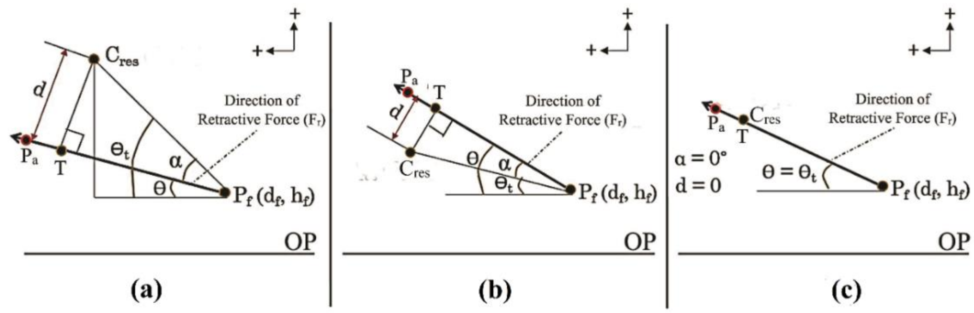

Figure 3: Position of retractive force (F_r) vector with respect to C_{res} for region [($d_f < d_c$) and ($h_f < h_c$)]; (a) Case I - F_r force vector passing occlusal to C_{res}[$\Theta < \Theta_t$], (b) Case II - F_r force vector passing apical to C_{res}[$\Theta > \Theta_t$], (c) Case III - F_r force vector passing through C_{res}[$\Theta = \Theta_t$].

In the region ($d_f < d_c$) and ($h_f < h_c$), there are three possibilities regarding position of retractive force F_r. The F_r force vector may pass occlusal to C_{res} or apical to C_{res} or through C_{res}. It depends on the positions of P_f, C_{res} and P_a. According to relative positions of these points, angle Θ varies accordingly. This demands different force system in this region according to position of F_r force vector. If $\Theta < \Theta_t$ (case I), the F_r force vector passes occlusal to C_{res} in this region. If $\Theta > \Theta_t$ (case II), the F_r force vector passes apical to C_{res} and if $\Theta = \Theta_t$ (case III), then only F_r force vector passes through C_{res}. Fig. 3a, 3b and 3c show the position of F_r force vector passing occlusal to C_{res},apical to $C_{res}$and through C_{res} respectively for the region [($d_f < d_c$) and ($h_f < h_c$)]. The direction of retractive force (F_r) vector (direction of teeth movement) is represented by line P_f-P_a.

For $\Theta < \Theta_t$ (case I), $\alpha = \Theta_t - \Theta$; For $\Theta > \Theta_t$ (case II), $\alpha = \Theta - \Theta_t$; For $\Theta = \Theta_t$ (case III), $\alpha = 0°$ (1)

$$\Theta = \tan^{-1}\left(\frac{h_a - h_f}{d_a - d_f}\right) \quad (2)$$

$$\Theta_t = \tan^{-1}\left(\frac{h_c - h_f}{d_c - d_f}\right) \quad (3)$$

$$P_f\,C_{res} = \left(\frac{h_c - h_f}{\sin(\Theta_t)}\right) \quad (4)$$

The perpendicular distance (d) between retractive force vector (F_r) and C_{res} is calculated as,

$$d = (P_f C_{res}) \times \sin(\alpha) \quad (5)$$

The moment (M_f) developed at C_{res} due to retrative force (F_r) is calculated as, Case (I): $M_f = +[F_r \times d]$;case (II): $M_f = -[F_r \times d]$;case (III): $M_f = 0$ (6)

The force system was considered to be viewed from the distal aspect of a right maxillary central incisor and all the points were considered to be projected on sagittal plane. From this viewing aspect, the positive (+) sign indicates clockwise directional moment and negative (–) sign indicates anti-clockwise directional moment.

The required counteracting moment (M_c) is calculated as,

Case (I) and (II): $M_c = -M_f$; case (III): $M_c = 0$ (7)

For this region $[(d_f < d_c)$ and $(h_f < h_c)]$, the value of M_c comes out to be negative (anti-clockwise direction) and positive (clockwise direction) for case (I) and (II) respectively. While in case (III), as $d = 0$, hence $M_c = 0$ (no counteracting moment is required).

2.2 Computer software

It is a tedious task to evaluate the magnitudes of parameters of required optimum force system manually for orthodontists from the devised set of equations. Hence, the computer software based on this mathematical computation was developed with the aid of Microsoft Visual Studio (version 2013, Microsoft Corporation, Redmond, Washington, USA) to estimate values of optimum force system. For this purpose, C++ programming language was used. The program incorporated in this computer software satisfies the aforementioned set of equations. Fig. 4 shows algorithmic flow-chart of the computer software. The steps of the algorithm are as follows:

First, the user of the software (orthodontist) needs to enter magnitude of retractive force (F_r) in grams and positions (co-ordinates) of P_f, P_a and C_{res} in mm. Then, the software displays the required counteracting moment (M_c) in gram-force mm (gf.mm) according to developed set of equations [eq. (1) to (7)].

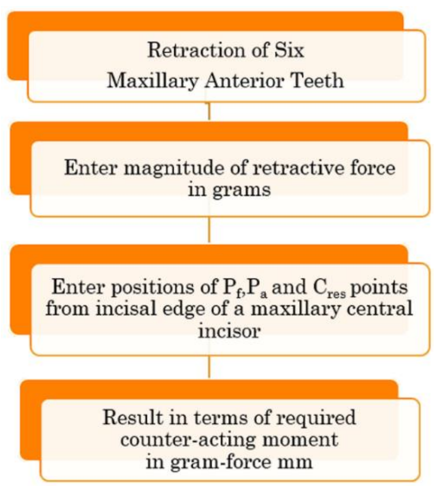

Figure 4: Algorithmic flow-chart of the developed computer software to evaluate the magnitudes of parameters of optimum force system.

Fig. 5 and 6 show all the two windows of the computer software. The values entered in these figures of software are for illustrative purpose only. Fig. 5 shows the first (start) window of the computer software. At topmost position of this window, the aim of the study is written that the retraction of six maxillary anterior teeth need to be achieved. The diagram is incorporated in this first window representing application of force system and generalized positions of different points. This diagram resembles with the Fig. 2. In this first window, all the input parameters need to be entered. So, the user needs to enter magnitude of retractive force (F_r) in grams. Additionally, the user needs to enter the positions of C_{res} of six maxillary anterior teeth, force application point (P_f) on these teeth and posterior teeth anchorage point (P_a) by entering their lingual and apical distance in mm with respect to incisal edge of a maxillary central incisor. The optimal position of C_{res} can be selected from previous research studies. Jeong et. al. [Jeong, Sung and Lee (2009)] reported that the C_{res} of six maxillary anterior teeth with normal inclination is generally 14 mm lingual and 13.5 mm apical to incisal edge of a maxillary central incisor. In this study, this position of C_{res} is considered to verify the mathematically computed force parameters by FEA. By clicking on the 'Proceed' button, the second (last) window of the software gets opened.

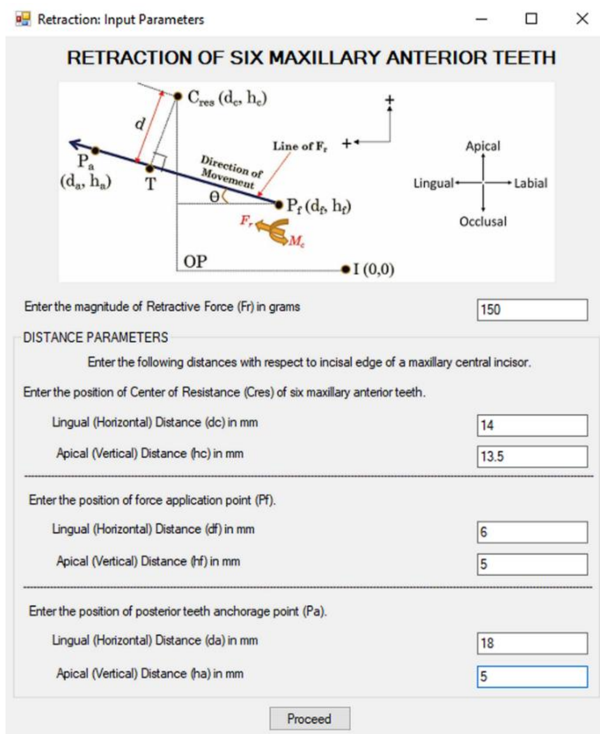

Figure 5: First (start) window of computer software for en-masse retraction of six maxillary anterior teeth.

Fig. 6 represents the second (last) window of the computer software. For the given value of retractive force (F_r) and other parameters, it displays the required counteracting moment (M_c) in gf.mm based on aforementioned developed set of equations. It also shows the nature of counteracting moment (positive for clockwise and negative for anti-clockwise) as viewed from the distal aspect of a right maxillary central incisor. It should be noted that this force system is applicable for half anterior teeth. Same force system should be applied on the other side of sagittal plane (bilaterally). By clicking on the 'Close' button, all the windows of the software get closed. To verify the computed optimum force system with this developed computer software based on the devised set of equations, FEA was performed.

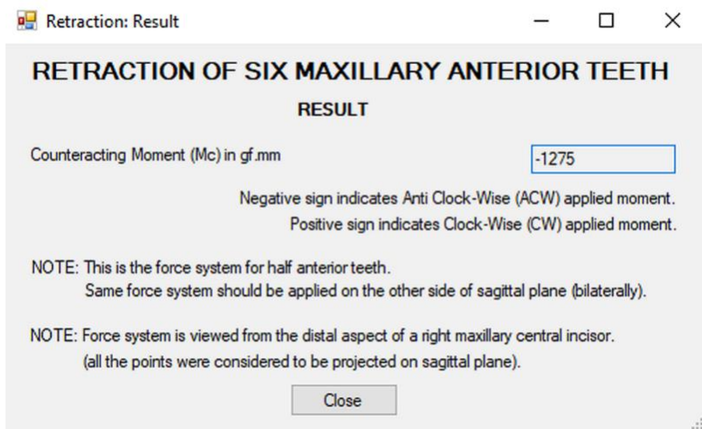

Figure 6: Second (last) window of computer software for en-masse retraction of six maxillary anterior teeth.

2.3 Verification of computed force system by finite element analysis

Three-dimensional computer aided design (CAD) models of six maxillary anterior teeth and surrounding structures of tissues i.e. Periodontal Ligament (PDL) and alveolar bone were modelled (Fig. 7). First, six maxillary anterior teeth with normal inclination were scanned using the CBCT (cone beam computed tomography) scan machine (Kodak 9000 extra-oral image system with 3D module, Version 2.2, Care stream Dental LLC, Atlanta, GA). Second, CAD model of six maxillary anterior teeth was generated from CT-scan (dicom) images using volume rendering process in MIMICS software (version 17, Materialise NV, Leuven, Belgium). Then, teeth surfaces were smoothed in MIMICS. The other surrounding structures were modelled in CREO software (version 2.0, PTC-Parametric Technology Corporation, Needham, Massachusetts, USA). This method of generating CAD model of teeth from CT scan data can be considered as reliable according to previous studies [Roostaie and Soltani (2017); Ghadiri, Shafiei and Salekdeh et al. (2016); Ji, Jiang and Tang et al. (2014)].

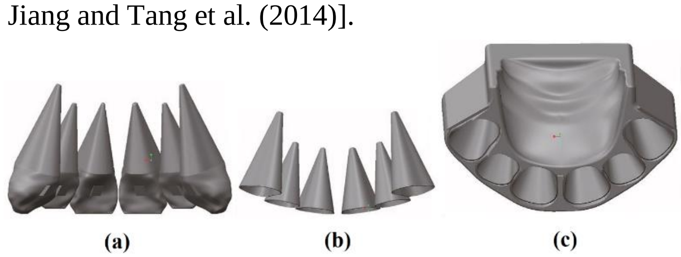

Figure 7: CAD models of six teeth structures; (a) maxillary anterior teeth, (b) periodontal ligament (PDL), (c) alveolar bone.

The teeth modelled in MIMICS were imported in CREO. The CAD models of other tissue structures i.e. PDL and alveolar bone were prepared using the reference of teeth model in CREO. The uniform thickness of PDL equal to 0.2 mm was considered in finite element analysis (FEA) [Thote, Uddanwadiker and Sharma et al. (2016); Thote, Sharma and Uddanwadiker et al. (2017)]. Two types of CAD models of brackets with archwire were prepared, one without power arm and other with power arm. Fig. 8 shows the assembly model of six maxillary anterior teeth with and without power arm on dental archwire in LiO. The purpose of consideration of power arm was to apply the force more apically (near to C_{res}).

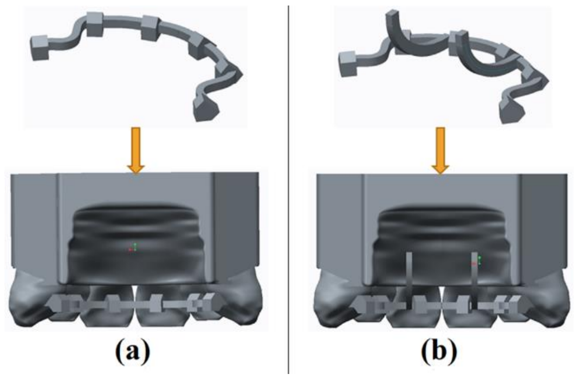

Figure 8: Assembly model of six maxillary anterior teeth in LiO; (a) archwire without power arm, (b) archwire with power arm.

Fig. 9 shows the distal and labial view of the assembly model of six maxillary anterior teeth. The bonded contact was specified between all the teeth structures in CREO. The assembly models were saved in STEP file format in CREO and imported into ANSYS.

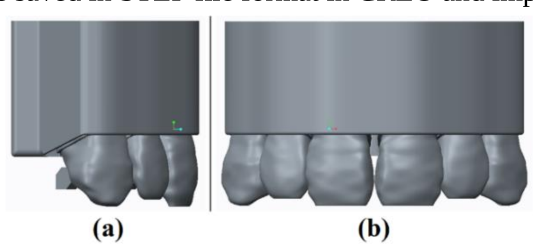

Figure 9: Assembly model of six maxillary anterior teeth; (a) distal view, (b) labial view.

In this study, ANSYS Workbench (version 16, ANSYS Inc., Canonsburg, Pennsylvania, USA) was used to verify the computed optimum force system by FEA. Total four assembly models were prepared. The refined meshing was applied on each assembly model with 10 node tetrahedral and 20 node hexahedral elements joined by nodes. On an average, one assembly model had 1,40,163 nodes and 74,869 elements. The brackets, archwire and power arms were considered in FEA for the application of force system at different positions. Hence, the force application point (P_f) was selected completely on the basis of anatomy, without considering type of brackets and archwire.

To apply boundary conditions, the lateral and upper surfaces of the alveolar bone holding maxillary anterior teeth were fixed in ANSYS Workbench. The maxillary anterior teeth, alveolar bone, brackets, archwire and power arms were considered to be linear elastic and isotropic in nature. While, the nature of PDL was considered to be non-linear and hyper-elastic. The material of lingual brackets, archwire and power arms was considered as stainless steel. Table 2 shows material properties of the teeth structures considered for FEA [Thote, Uddanwadiker and Sharma et al. (2016); Thote, Sharma and Uddanwadiker et al. (2017)].

Table 2: Material properties of teeth structures

No.	Material	Young's Modulus [MPa]	Poisson's Ratio
[1]	maxillary anterior teeth	19600	0.30
[2]	alveolar bone	13700	0.26
[3]	brackets, archwire and power arms (stainless steel)	200000	0.30

It was proved from previous studies that the assumption of non-linear nature of PDL shows more realistic results [Toms and Eberhardt (2003); Pietrzak, Curnier and Botsis et al. (2002); Bergomi, Cugnoni and Galli et al. (2011); Huang, Tang and Tan et al. (2017)]. Fig. 10 represents the uniaxial non-linearity of PDL in the form of stress-strain curve obtained from previous FEA studies [Thote, Sharma and Uddanwadiker et al. (2017); Cattaneo, Dalstra and Melsen (2005); Uddanwadiker, Padole and Arya (2007)]. The curve indicates strain values up to 93% in compression and up to 100% in tension. This non-linear behavior of PDL represents hyper-elasticity [Qian, Todo and Morita (2009)]. Though several constitutive PDL models have been developed by researchers to represent its hyper-elastic nature, the Mooney-Rivlin hyper-elastic model can be considered as more appropriate for this stress-strain curve as strain level is up to 100% [Kumar and Rao (2016)].

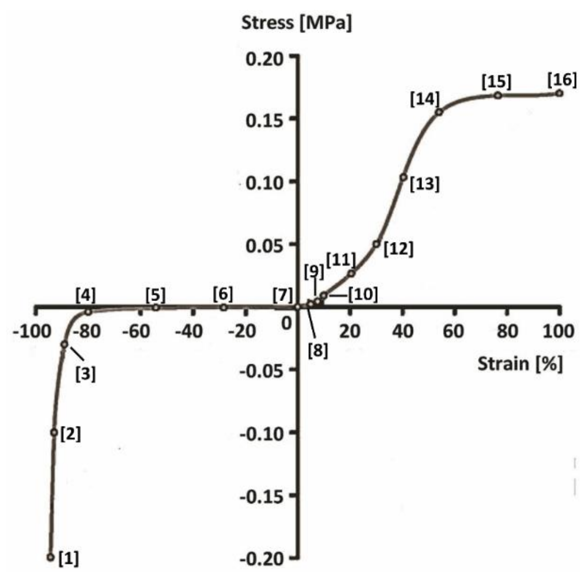

Figure 10: Stress-strain curve representing uniaxial non-linearity of PDL.

Total 16 points (encircled and numbered in Fig. 10) were picked from the stress-strain curve and entered as uniaxial and hyper-elastic data of PDL in ANSYS Workbench as shown in Table 3. The different Mooney-Rivlin parameter models (2, 3, 5 and 9 parameters) were used to obtain the best fit curve for this stress-strain curve. As the best fit curve was obtained in the case of Mooney-Rivlin 2-parameter model, it was selected to indicate non-linearity and hyper-elasticity of PDL. The curve fit for Mooney-Rivlin 2-parameter model was solved and the material constants were evaluated in ANSYS Workbench as: $C_{01} = -0.0972$ MPa and $C_{10} = 0.1137$ MPa. In this way, non-linearity and hyper-elasticity of PDL was represented in ANSYS Workbench. Then, the results of FEA were obtained by execution of solution command.

Table 3: Points picked from uniaxial and non-linear stress-strain curve

Points	**Stress [MPa]**	**Strain [%]**
[1]	–0.200	–93
[2]	–0.100	–91
[3]	–0.030	–89
[4]	–0.010	–80
[5]	–0.004	–55
[6]	–0.002	–28
[7]	0.000	0
[8]	0.003	5
[9]	0.006	8
[10]	0.010	10
[11]	0.025	20
[12]	0.050	30
[13]	0.100	40
[14]	0.150	55
[15]	0.170	77
[16]	0.175	100

In FEA, the value of F_r was kept fixed i.e. 150 g (1.5 N) and M_c was calculated from the computer software by varying other input parameters. For these CAD models of maxillary anterior teeth with normal inclination, the C_{res} was considered to be 14 mm lingual and 13.5 mm apical to the incisal edge of a maxillary central incisor i.e. $d_c =$ 14 mm and $h_c = 13.5$ mm [Jeong, Sung and Lee (2009)]. To verify the retraction movement, two positions of P_f and P_a were considered. Thus, total four analyses were performed and hence, four assembly models were prepared. For this purpose, four sets of input parameters were considered to compute optimum force system from computer software as shown in Table 4. The height of archwire level was considered to be 5 mm from occlusal plane (OP). Hence, for sets [a] and [b] of input parameters, assembly model without power arm was used as h_f was equal to the height of archwire level. While, for sets [c] and [d] of input parameters, assembly model with power arm was used as h_f was greater than the height of archwire level. As shown in Table 4, the value of angle of retractive force (Θ) was computed from Eq. (2). For sets [a] and [c] of input parameters, the value of Θ equal to 0˚ (Table 4) indicates that the retraction parallel to occlusal plane should take place. While, for sets [b] and [d] of input parameters, the value of Θ greater than 0˚ (Table 4) indicates that the retraction inclined to occlusal plane should take place. The computer software computes the value of Θ from the other input parameters but does not display it. It only displays the required value of counteracting moment (M_c) which is required to orthodontists.

Table 4: Input parameters considered to compute optimum force system from computer software

No.	**Retractive Force (F_r)**	**Position of center of resistance (C_{res})**	**Position of force application point (P_f)**	**Position of posterior teeth anchorage point (P_a)**	**Angle of retractive force (Θ) in degrees**
[a]	150 grams	$d_c = 14$ mm, $h_c = 13.5$ mm	$d_f = 6$ mm, $h_f = 5$ mm	$d_a = 18$ mm, $h_a = 5$ mm	0˚
[b]	150 grams	$d_c = 14$ mm, $h_c = 13.5$ mm	$d_f = 8$ mm, $h_f = 5$ mm	$d_a = 20$ mm, $h_a = 9$ mm	18.4˚
[c]	150 grams	$d_c = 14$ mm, $h_c = 13.5$ mm	$d_f = 6$ mm, $h_f = 8$ mm	$d_a = 18$ mm, $h_a = 8$ mm	0˚
[d]	150 grams	$d_c = 14$ mm, $h_c = 13.5$ mm	$d_f = 8$ mm, $h_f = 8$ mm	$d_a = 20$ mm, $h_a = 12$ mm	18.4˚

For each set of input parameters, the required counteracting moment (M_c) obtained from the computer software is shown in Table 5. The negative (–) sign of M_c indicates that it should be applied in anti-clockwise direction as viewed from the distal aspect of a right maxillary central incisor. This force system (F_r and M_c) was applied in FEA accordingly.

Table 5: Required counteracting moment (M_c) obtained from the computer software

No.	**Counteracting moment (M_c)**
[a]	–1275 gf.mm
[b]	–925 gf.mm
[c]	–825 gf.mm
[d]	–498 gf.mm

3 Results

According to different sets of input parameters, the parameters of optimum force system were computed from the computer software (Table 4 and 5) and applied the same in ANSYS Workbench to perform FEA. Fig. 11 shows vectors of nodal displacements along with undeformed (d_1) and deformed (d_2) models indicating en-masse retraction of six maxillary anterior teeth in LiO for all the four sets of input parameters.

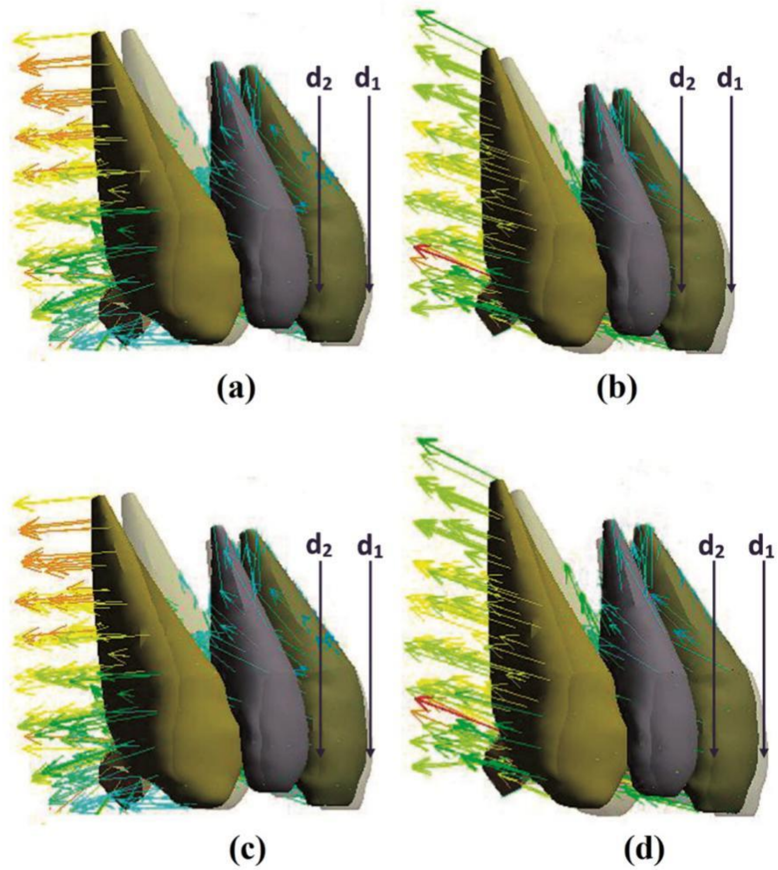

Figure 11: Vectors of nodal displacements along with undeformed (d_1) and deformed (d_2) models indicating en-masse retraction of six maxillary anterior teeth in LiO for all the four sets of input parameters; (a) set [a], (b) set [b], (c) set [c], (d) set [d].

For sets [a] and [c] of input parameters where $\Theta = 0^{\circ}$ (Table 4), the desired retraction parallel to occlusal plane was achieved as observed from the vectors of nodal displacements as well as positions of undeformed and deformed models. While, for sets [b] and [d] of input parameters, the retraction inclined to occlusal plane was achieved with $\Theta = 18^{\circ}$ in FEA which matches approximately with the theoretical value of $\Theta = 18.4^{\circ}$ (Table 4) and hence, it can be considered as acceptable. So, it was clear that the desired en-masse retraction of six maxillary anterior teeth in LiO was achieved for each set of input parameters. Thus, it can be said that, the optimum force system obtained from computer software (based on the mathematical computation) was verified with FEA.

4 Discussion

Previous researchers also stated different methods of retraction of maxillary anterior teeth. Shroff et al. [Shroff, Yoon and Lindauer et al. (1997)] corrected deep overbite using different combinations of archwire. But, only one case was reported in their study. Hence, their study cannot be applied widely. Park et al. [Park, Choi and Choi et al. (2007)] achieved segmented retraction of maxillary anterior teeth by orthodontic mini-implants and palatal appliance. But, maintaining of normal inclination of teeth was difficult in the study of Park et al. [Park, Choi and Choi et al. (2007)] as only retractive force was applied by them. Kim et al. [Kim, Suh and Kim et al. (2010)] stated the required height of power arm to achieve retraction of maxillary anterior teeth by FEA. Additionally, other studies [Sung, Jang and Chun et al.(2010); Chetan, Keluskar and Vasisht et al. (2014)] also developed different methods to achieve retraction of maxillary anterior teeth by FEA only. However, outcomes of these studies were completely dependent on FEA results only. In our study, parameters of optimum force system were computed mathematically and a computer software was developed based on this mathematical computation. The C++ program incorporated in developed computer software satisfies the devised mathematical set of equations. Then, FEA was used to verify the force parameters obtained from a computer software.

In this study, force parameters were computed mathematically so that a single retractive force should act through C_{res} to achieve en-masse retraction of six maxillary anterior teeth in LiO. Application of these force parameters (F_r and M_c) should be bilateral with respect to sagittal plane. Sometimes, power arms are also used for application of force system. This increases the height of P_f from occlusal plane (OP).

The developed computer software satisfies the devised set of equations. As position of P_f is generally labial and occlusal to C_{res}, set of equations is developed only for this region. The force system was considered to be viewed from the distal aspect of a right maxillary central incisor and all the different points were considered to be projected on sagittal plane. In the computer software, the direction of evaluated counteracting moment (M_c) was considered from this viewing aspect. From the evaluated value of M_c, orthodontists can decide proper combination of bracket slot size and archwire dimensions which yield required value of M_c.

For verification of computed force system by FEA, the value of retractive force (F_r) was selected to be 150 grams from previous studies [3, 26]. In FEA, the position of C_{res} was considered to be 14 mm lingual and 13.5 mm apical to the incisal edge of a maxillary central incisor i.e. C_{res} (14, 13.5) for normal inclination of maxillary anterior teeth [Jeong, Sung and Lee (2009)]. While, an orthodontist can select any other suitable values of F_r and C_{res}. The computer software calculates the required counteracting moment according to values of considered input parameters in this study.

In FEA, two values of P_f and $P_a$were selected. Thus, total four sets of input parameters were considered. All these positions were selected randomly only for verification of obtained force parameters from computer software by FEA. The results of teeth movement in terms of vectors of nodal displacements along with undeformed (d_1) and deformed (d_2) models showed that the en-masse retraction of six maxillary anterior teeth in LiO was achieved. In this way, the computed optimum force system was verified with

FEA.

The developed computer software has certain advantages. It is developed to simplify the estimation of force parameters for orthodontist. The computer software is also user-friendly. In computer software, the user can enter any suitable position of C_{res} according to perception of each orthodontist or previous research studies. This makes the computer software more generalized and applicable to estimation of optimum force system for variety of patients. In future, new lingual appliances can be designed based on this study.

In previous studies, no other researcher has developed a computer software to estimate optimum force system for en-masse retraction as per our knowledge. In this study, the developed software has limited application. It is applicable to achieve en-masse retraction of six maxillary anterior teeth. In future, we will extend this computer software by including more types of orthodontic movements. However, in-vivo experimental validation of this study is needed before clinical application.

5 Conclusion

To achieve en-masse retraction of six maxillary anterior teeth in LiO, the optimum force system was devised mathematically.

- The mathematical set of equations was devised to evaluate the required counteracting moment (M_c) in gram-force mm (gf.mm) from the magnitude of retractive force (F_r) in grams and other input parameters.
- The developed computer software accurately estimates the required force system according to mathematical computation and it is generalized to incorporate any suitable values of input parameters.
- The developed computer software simplifies the task of computation for orthodontists. The orthodontists can easily operate this computer software as it is user-friendly.
- Further, in-vivo validation of this study is required in future before clinical application.

If this study is established as a treatment methodology, it is anticipated that the en-masse retraction of six maxillary anterior teeth in LiO will be achieved quite smoothly and efficiently by minimizing the treatment time.

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