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Comparative evaluation of dental, dentoalveolar and skeletal effects of slow maxillary expansion using Jackscrew, Quadhelix and Niti palatal expander2 on a finite element model of a young skull

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Abstract

Introduction: Slow expansion is a routine procedure for space gaining in Orthodontics. Jack Screw, Quadhelix and NiTi palatal expander-2 are commonly used slow expansion devices with a varied degree of dental and skeletal effects. Finite element method is a well- established technique to analyze stress and deformation in the craniofacial region in three dimensions after application of orthodontic forces. This study was aimed to evaluate and compare the dental, dento-alveolar and skeletal effects of the three slow expansion devices: Jackscrew, Quad helix and NiTi expander-2 on a young maxillary bone using a finite element model.

Materials and Method: The 3D finite element model was developed after scanning a dried human skull of mixed dentition with white light scanner. The mechanical properties of the teeth, bone and sutures were defined for the analytical model and subjected to forces by three expansion devices to compare their dental, dento-alveolar and skeletal effects.

Results: All the three expansion devices show significant difference in overall stress distribution and deformation in X and Y axis whereas equal efficiency in Z-axis. All the three devices showed significant differences in dental, dento-alveolar and skeletal effects where, Jackscrew showed highest deformation in X axis in the dental region and highest deformation in Y and Z axis in the dento-alveolar region.

Conclusion: The highest values of stress and strain are shown by Jackscrew, followed by Quadhelix and lastly by NiTi palatal expander-2 where Quadhelix and NiTi expander-2 showed almost similar performance.

Keywords: Slow maxillary expansion, FEM study, Stress distribution, Deformation

Introduction

Expansion as an early treatment strategy during mixed dentition benefits an estimated 25% to 30% of all orthodontic patients.(1) Expansion across the mid-palatine suture can be done in two ways, rapid and slow, depending upon the speed at which it is carried out.

Rapid expansion exerts forces from 3-20 pounds causing 1 mm expansion per day. Rapid expansion is uncomfortable and painful to the patient and also invites high rates of relapse.(2) On the contrary, slow expansion exerting about 2 pounds of force and causing 1mm of expansion per week provides approximately the same amount of skeletal and dental expansion over a 10-12 week period as rapid expansion. Slow expansion can even produce widening of the mid-palatine suture at a rate close to the maximum speed of bone formation and thus it is more physiologic.(3) Routinely used slow expansion devices are Jack Screw, Quad helix and Niti palatal expander2. Jack screw embedded in a split acrylic plate is a commonest and oldest form of slow expansion device as developed by Martin Schwarz.(4) The screw when opened one-quarter turn causes 0.5 mm expansion. It expands the arches by 1mm when two quarter turns are opened. Quad helix was designed by Dr Ricketts.(5) He discovered and proved using laminograph x-rays that quad helix exerts a palatal suture widening. He showed new bone remodelling at the suture and also showed that sutural separation was in pace with the speed of new bone formation. The nickel titanium palatal expander2 as introduced by Wendell V. Arndt(6) delivers a uniform, slow, continuous force for maxillary expansion. The transition temperature of the expander set at 94ºF facilitates harnessing its properties of shape memory at oral cavity temperature. The appliance expands at a rate that maintains tissue integrity. In other words, as the palate expands, regeneration of the bone matches the rate of expansion.

The finite element method (FEM) today is considered an established technique for computer solution of complex problems in fields of engineering as well as in medical and dental research. A major advantage of this method is possibility of simulating treatment approaches without exposing animals or humans to experimental procedures. This method has been successfully used to analyze the effects of expansion on teeth and craniofacial bones.(7-9) It allows accurate mathematical calculation of stress and strain on the anatomic structures which as such is not possible with clinical studies.

A lot of research has been found assessing and comparing expansion devices using clinical(10-13), and photoelastic(14) methods, but except one(9) no other studies have been conducted in which the effects of slow expansion devices are compared using finite element method. Thus, an attempt was made to evaluate and compare the three dimensional dental, dento-alveolar and skeletal effects of three slow expansion devices commonly used in orthodontics namely Jack screw in acrylic plate, Quad helix and NiTi palatal expander2 using finite element method.

Materials and Method

The study was conducted at Milestone PLM solution private limited, Mumbai. The 3D finite element model was developed after scanning a dried human skull of mixed dentition period about 8- 10 years of age estimated from status of dentition as visible on the skull with a white light scanner using a technology called reverse engineering with the help of software 'ANSYS version 14.' The skull was scanned creating a point cloud which was then converted into polygon/triangle mesh model using Delaunay triangulation method and a geometric model was created.

The next step was to convert the 3D geometric model into finite element model (Fig. 1). The complete geometric model was an assemblage of discrete pieces called elements and were connected together at finite number of points called nodes. In the present study, the total number of elements and nodes were 39858 and 658799 respectively. The mechanical properties of teeth, compact & cancellous bone and sutures was defined (Table 1) for the analytical model which was then subjected to forces exerted by three expansion devices namely Jack screw in split acrylic plate, Quad helix and NiTi palatal expander2 to evaluate and compare their dental, dento-alveolar and skeletal effects on the craniofacial skeleton.

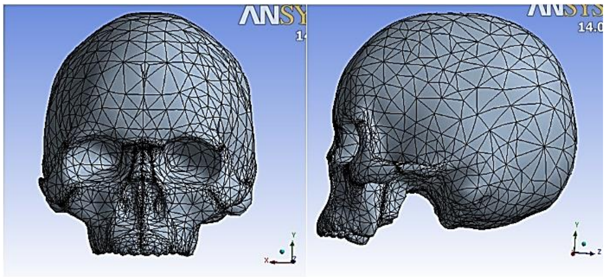

Fig. 1

Table 1: Young's modulus and Poisson's ratio of various materials used in this study

Materials	Young's modulus		Poisson's ratio
	N/mm^2	Mpa	
Teeth[15]	20×10^3	20000	0.3
Compact bone,[15,16]	9.04×10^3	9042	0.3
Cancellous bone[15]	7.9×10^2	7900	0.3
Suture[17]	6.9	6.9	0.49
Acrylic[18]	2400	2400	0.35
Nickel titanium[18]	110×10^3	110000	0.35
Stainless steel (AISI 304 steel)[8]	190×10^3 - 210×10^3	190000-210000	0.3

After defining mechanical properties to the model, appropriate boundary conditions were laid down. Restrains were established at all the nodes of the cranium except on the nodes of anatomic landmarks where stress distribution and deformation was to be studied.

The designs of each appliance were programmed in the software. The three expansion devices were activated as per their standard protocol. The Jackscrew in split acrylic plate was activated by moving apart the two acrylic plates by 1mm. Quad helix was activated by 4 mms exerting 495 gms of total force as per its initial activation protocol.(19) The NiTi palatal expander2 has a pre-programmed force application of producing 350 gms of force with every 3mm of expansion.(20)

The Von Mises stress distribution in Mpa and displacement in millimetres (mms) were noted at various dental, dento-alveolar and skeletal landmarks in three different directions namely; transverse (X), vertical (Y) and sagittal (Z) and analysed statistically using SPSS software version 17.

Results

Table 2: Values of Stress Distribution by Jackscrew, Quadhelix and Niti Expander2 at each selected anatomic landmark (Fig. 2)

Regions	Selected anatomic landmarks (N=21)	Stress distribution (Von Mises stress) Mpa		
		Jack screw	Quadhelix	NiTi Expander2
Dental	Contact point between central incisors	18.19	0.35	0.25
	Cusp tip of canines	18.95	0.17	0.10
	Central pit of first permanent molars	117.3	71.1	35.84
	CEJ of central incisors	21.59	0.41	0.29
	CEJ of canines	21.86	0.18	0.14
	CEJ of first permanent molars	119.9	74.7	37.63
Dentoalveolar	Apical region of central incisors	22.08	3.04	3.31
	Apical region of canines	23.62	4.12	4.01
	Apical region of first permanent molars	29.32	7.93	6.20
Skeletal	Midpalatine suture -anterior tip	56.8	33.2	17.8
	Posterior end	2.20	3.4	2.40
	Anterior nasal spine	47.68	10.31	5.20
	Nasal septum	28.90	12.78	6.28
	Internasal suture	9.80	2.789	1.8
	Nasomaxillary suture	11.32	2.90	1.99
	Frontonasal suture	3.90	0.58	0.41
	Frontomaxillary suture	3.80	0.68	0.46
	Zygomaticomaxillary suture	5.10	1.40	0.49
	Zygomaticofrontal suture	5.001	2.30	1.70
	Zygomaticotemporal suture	0.67	0.22	0.13
	Pterygomaxillary suture	2.66	9.27	6.63

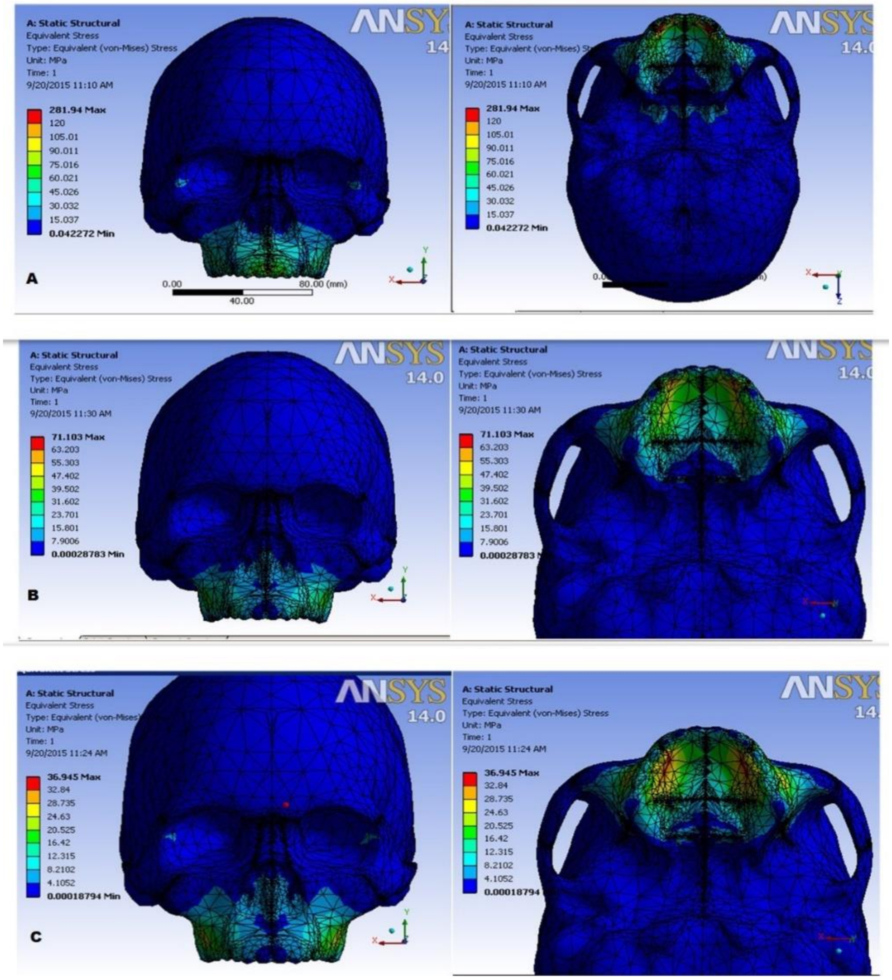

Fig. 2: Stress distribution at all the anatomic landmarks in all the three axes by (A) Jackscrew, (B) Quadhelix and (C) Niti Palatal Expander2

Table 3: Mean values of stress distribution by the three expansion devices in dental, dentoalveolar and skeletal regions

Expansion Device	Region	Mean Mpa	Std. Deviation	N
Jackscrew	Dental	52.96	50.868	6
	Dento Alveolar	25.01	3.814	3
	Skeletal	13.15	18.636	12
	Total	91.12	34.009	21
Quad Helix	Dental	24.48	37.519	6
	Dento Alveolar	5.03	2.569	3
	Skeletal	6.65	9.355	12
	Total	36.16	21.718	21
NiTi Exp-2	Dental	12.39	18.865	6
	Dento Alveolar	4.51	1.508	3
	Skeletal	3.77	4.980	12
	Total	20.67	10.876	21

Table 3 shows Jackscrew producing highest values of stress at each dental, dento-alveolar and skeletal regions after activation. All the three devices show highest stress at the dental region. The stress distribution at the skeletal landmarks is also noticeable by all the three devices.

Table 4: Two way anova between expansion devices and region for stress distribution

Source	Type III Sum of Squares	Df	Mean Square	F	p-value
Corrected Model	12541.010	8	1567.626	3.152	0.005*
Intercept	12510.511	1	12510.511	25.153	0.000*
Expansion Device	4699.311	2	2349.656	4.724	0.013*
Region	5960.345	2	2980.172	5.992	0.004*
Expansion device * Region	2112.979	4	528.245	1.062	0.384
Error	26857.914	54	497.369		
Total	52998.780	63			
Corrected Total	39398.924	62			

R Squared = .318 (Adjusted R Squared = .217) *The difference is significant at $P \leq 0.05$

Table 4 describes that all the three expansion devices show significant difference in producing stress distribution in dental, dento-alveolar and skeletal areas (P=0.013). All the three regions also show a significant difference in stress distribution after activation of the three expansion devices (P=0.004).

Table 5: Tukey's Post Hoc test for multiple comparisons between the three expansion devices for stress distribution in all the three areas

Expansion Device		Mean Difference	Std. Error	p-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Jackscrew	Quad Helix	14.71	6.882	.092	-1.88	31.29
	NiTi	19.88*	6.882	.015*	3.29	36.47
Quad Helix	NiTi	5.17	6.882	.734	-11.41	21.76

*The difference is significant at $P \leq 0.05$

Table 5 shows that Jackscrew produces maximum stress in all the three regions followed by Quadhelix and the NiTi palatal expander 2, where Quadhelix and NiTi expander2 produce almost equal stress with P=0.734.

Table 6: Displacement in millimetres In X (Transverse), Y(Vertical), And Z(Sagittal) Axis By All the three expansion devices at all the selected landmarks (Fig. 3)

Region	Selected anatomic landmarks	Jack screw			Quad helix			Niti Expander2		
		X	Y	Z	X	Y	Z	X	Y	Z
Dental	Contact point between central incisors	0.78	-0.54	0.004	0.125	-0.07	0.0007	.07	-.04	.0002
	Cusp tip of canines	0.59	-0.45	0.07	0.008	-0.008	0.15	.01	-.008	.05
	Central pit of first permanent molars	0.46	-0.34	0.24	0.03	-0.01	0.19	.02	-.01	.14
	CEJ of central incisors	0.62	-0.51	0.003	0.112	-0.069	0.0006	.06	-.03	.0002
	CEJ of canines	0.54	-0.39	0.051	0.004	-0.0007	0.11	.01	-.006	.03
	CEJ of first permanent molars	0.41	-0.31	0.19	0.028	-0.008	0.15	.019	-.01	.11
Dento alveolar	Apical region of central incisors	0.301	-0.58	0.18	0.04	-0.04	0.16	.01	-.021	.11
	Apical region of canines	0.27	-0.592	0.192	0.06	-0.03	0.18	.02	-.015	.12
	Apical region of first permanent molars	0.23	-0.612	0.162	0.08	-0.01	0.151	.03	-.009	.102
Skeletal	Midpalatine suture -anterior tip	0.35	-0.33	0.001	0.05	-0.03	0.0005	.03	-.02	.0007
	Posterior end	0.24	-0.19	0.001	0.001	-0.004	0.00002	.01	-.003	.0002
	Anterior nasal spine	0.24	-0.44	0.003	0.07	-0.08	0.0003	.003	-.04	.0001
	Nasal septum	0.17	-0.3	0.002	0.05	-0.002	0.0002	.04	-.01	.00008
	Internasal suture	0.09	0.31	0.001	0.0003	-0.007	0.0001	.0003	.0005	.00006

	Nasomaxillary suture	0.09	0.31	0.02	0.0002	0.007	0.0006	.0002	.00002	.0003
	Frontonasal suture	0.07	0.30	0.001	0.0005	0.004	0.000008	.0003	.002	.000006
	Frontomaxillary suture	0.07	0.29	0.0007	0.0005	0.003	0.00003	.0004	.002	.00002
	Zygomaticomaxillary suture	0.13	-0.34	0.011	0.007	-0.02	0.004	.005	-.02	.0001
	Zygomaticofrontal suture	0.06	-0.27	0.009	0.0008	-0.009	0.003	.006	-.006	.002
	Zygomaticotemporal suture	0.16	-0.27	0.015	0.001	-0.01	0.0001	.009	-.009	.0002
	Pterygomaxillary suture	-0.294	0.21	0.001	-0.023	0.012	0.004	-.007	.007	.004

The negative value of Y-axis denotes downward vertical displacement of the anatomic landmarks.
The positive value of Z- axis denotes anterior displacement of the anatomic landmarks.

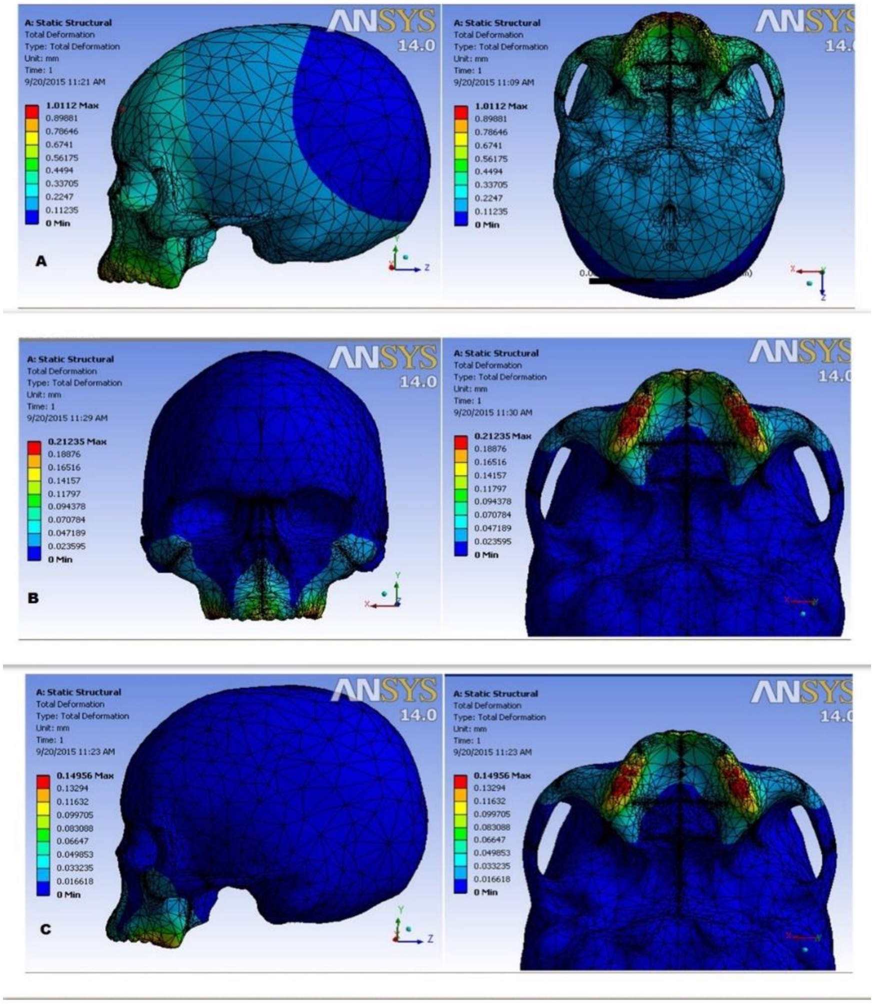

Fig. 3: Deformation at all the anatomic landmarks in all the three axes by (A) Jackscrew, (B)Quadhelix and (C) Niti palatal Expander 2

Table 7: Mean displacement by all the expansion devises in all the three axes

Expansion Device	Region	N	X axis		Y axis		Z axis	
			Mean mm	SD	Mean mm	SD	Mean mm	SD
Jackscrew	Dental	6	.57	.131	-.42	.092	.09	.099
	Dento Alveolar	3	.11	.298	-.59	.016	.18	.015
	Skeletal	12	.11	.156	-.06	.310	.01	.007
	Total	21	.79	.265	-1.07	.322	.28	.082
Quad Helix	Dental	6	.05	.053	-.03	.033	.10	.081
	Dento Alveolar	3	.06	.020	-.03	.015	.16	.015
	Skeletal	12	.01	.028	-.01	.025	.00	.002
	Total	21	.12	.040	-.07	.026	.26	.076
NiTi Expander2	Dental	6	.03	.026	-.02	.014	.06	.058
	Dento Alveolar	3	.02	.010	-.02	.006	.11	.009
	Skeletal	12	.01	.014	.00	.013	.00	.001
	Total	21	.06	.020	-.04	.013	.17	.050

The Table 7 reveals jackscrew showing maximum expansion of 0.57 mm (X axis) in dental region and highest downward descent of -0.59 mm (Y axis) and highest forward sagittal displacement of 0.18 mm (Z axis) in the dentoalveolar region.

One way Anova was performed to compare the performance of the three devices for deformation in X, Y and Z axis. In X and Y axis, the three devices showed significant difference at $p<0.001$ but in Z axis, the Anova results were not significant with $p=0.510$ indicating that all the three devices showed equal performance in Z axis i.e. forward sagittal displacement. Thus, further Tukey's Post Hoc test was done only for X and Y axis to compare the performance of the three devices.

Table 8: Tukey's Post Hoc Test for Multiple Comparisons of Displacement in X and Y Axis between the Three Expansion Devices

Axis	Device		Mean Difference	Std. Error	P-value	95% Confidence Interval	
						Lower Bound	Upper Bound
X axis	Jackscrew	Quad Helix	.213*	.048	.000*	.10	.33
		NiTi Exp2	.227*	.048	.000*	.11	.34
	Quad Helix	NiTi Exp2	.014	.048	.953	-.10	.13
Y axis	Jackscrew	Quad Helix	-.222*	.058	.001*	-.36	-.08
		NiTi Exp2	-.229*	.058	.001*	-.37	-.09
	Quad Helix	NiTi Exp2	-.006	.058	.993	-.14	.13

*The difference is significant if P value is ≤0.05

As seen in Table 8 Jackscrew shows significant difference with Quadhelix and NiTi expander2 at P= 0.000 with highest value of deformation in X axis i.e. transverse expansion (0.24mm), followed by Quadhelix and lastly by NiTi expander-2 where Quadhelix and NiTi expander-2 show almost equal performance (P=0.953).

Further, as seen in Table 8 Jackscrew shows significant difference with Quadhelix and NiTi expander2 at P= 0.001 with highest value of deformation in Y axis i.e. vertical displacement (-0.24mm), followed by Quadhelix and lastly by NiTi expander 2 where Quadhelix and NiTi expander2 show almost equal performance (P=0.993).

Discussion

In the present study, a mixed dentition skull with an approximate age of 10 years was scanned to reconstruct a 3D finite element model. The point of force application, magnitude and direction of force with all the three devices was simulated as per the clinical situation. The stress distribution and deformation produced from dental and dentoalveolar structures to various craniofacial sutures was measured and analyzed.

The Finite Element method is an accurate theoretic prediction research tool. But the results of any simulated study have to be confirmed with other experimental or clinical studies. The validation of the results of this FEM study were confirmed with previously published human[2,21-23] and FEM studies.[7-9,24] The earlier human and animal studies were done using high degree of forces which allowed clinical visualization of dental and skeletal effects but the slow expansion devices used in the present study exert very low degree of forces. The stress and strain effect of such appliances on dental and surrounding structures and their comparison is not possible clinically. The Finite Element Model was successfully used in the present study to achieve the desired goal.

Looking at the findings in Table 2, it can be noted that stress is observed on all the landmarks including the skeletal landmarks, confirming the skeletal effect of slow expansion devices by previous studies of Chaconas and Caputo[14] and Preeth.[9] Comparing stress distribution at different landmarks (Table 2), it is the molar at CE junction, which shows the highest stress concentration as it is the area where all the three appliances are anchored. These findings are also in accordance with that by Chaconas and Caputo[14], by Iseri[24] and also by Alireza[7] and Preeth.[9] Amongst skeletal landmarks, the anterior tip of the mid-palatine suture shows the highest stress concentration with all the three expansion devices which substantially reduces towards the posterior end. These findings are also in accordance with that by all the previous studies where stress is calculated at different sites.

Further in Table 3, it can be seen that Jackscrew shows highest degree of stress (91.12 MPa) in all the three regions, followed by Quad helix (36.16MPa) and lastly by NiTi Expander2 (20.67MPa). These findings are in accordance with the results of Chaconas and Caputo[14] who stated that a stable removable appliance produces more stress as compared to fixed appliances like Hass, Hyrax, Minne expander and Quad helix.

Discussing about deformation in X axis (transverse), the 'V'-shaped skeletal deformation is evident both in the anteroposterior and vertical plane by all the three devices (Table 7). This 'V' shaped deformation is supported by previous studies[7,22-29] where broader part of 'V' is located anteriorly and inferiorly. Further from Table 7, it can be stated that Jackscrew shows maximum transverse expansion, followed by Quadhelix and finally NiTi expander2 in dental (0.57mm), dentoalveolar (0.11mm) as well as skeletal (0.11mm) regions. This is in confirmation with Chaconas and Caputo[14] who found jackscrew producing more expansion than Quad helix and also by Preeth[9] who found Jackscrew producing more expansion than NiTi expander. Further, comparing the three devices for their impact in X-axis (Table 8), Quadhelix and NiTi expander2 show almost equal performance with P= 0.953. This result coincides with that of Donohue[11] who compared Quad helix and NiTi Expander for their clinical performance and concluded that both the devices are equally efficient maxillary expanders.

Finally in Table 8, comparing the three devices for downward vertical deformation(Y axis), all show a significant difference. The highest deformation is produced by Jackscrew and again Quadhelix and NiTi expander2 show almost the same vertical deformation with P= 0.993. In the present study, like other previous studies[22-27,30,31] the maxilla, point ANS and the maxillary teeth all show a downwards displacement.

Summarizing the results of the present study, for the overall and region-wise stress distribution and deformation, Jackscrew showed the highest values, followed by Quad helix and lastly the NiTi palatal expander2, confirming the findings of previous studies.[9,14] The reason being Jackscrew in an acrylic plate is anchored and closely adopted along the CE junction of the entire dentition thus producing a greater impact whereas the other two devices are anchored mainly on the first molars and lack such a close proximity and that is the reason that though the initial force activation is larger with these two devices their impact on the tissues is smaller. Finally, the Quadhelix and Niti palatal Expander2 showed almost equal performance in the present study and also by Donohue[11] in his clinical study. But as stated by Donohue, the selection from either of the two should be based on the fact that Quad helix shows more individual controlled and predictable expansion. Whereas Niti palatal expander2 should be selected when patient's comfort is of concern as this is the least stress producing device.

Conclusion

1. All the three slow expansion devices studied herein are capable of producing skeletal deformation apart from their known dental and dento-alveolar effects.
2. The highest value for stress distribution and deformation in X and Y axis is shown by Jackscrew, followed by Quadhelix and lastly by NiTi palatal expander 2 Where, Quadhelix and NiTi palatal expander2 show almost equal performance. All the three devices showed almost equal efficiency in Z axis.
3. In X axis, a significant deformation was shown by Jackscrew in dental region with the mean value of 0.57 mm. This was in accordance with 1 mm expansion incorporated in Jackscrew in the FEM model.
4. Thus, Jackscrew can be rated as the most efficient slow expansion device in terms of stress distribution and deformation. Quadhelix and NiTi palatal Expander 2 showed almost equal performance.

Here it is important to note that individual variability in anatomic structure and physiologic response can affect the response to the loading of these devices. This individuality is not possible in FEM study. Though this is a one-time study on a single human skull with a onetime activation of all the three devices, the results give a detailed insight into the initial mechanical response of the biological tissues of craniofacial region to slow expansion therapy and also helps understand and predict the compounded effects with subsequent activations.

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