Analysis of Biomechanical Effects of Different Sites and Modes of Orthodontic Loading On Arch Expansion in a Preadolescent Mandible: An FEA Study

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Introduction: *The aim of commencing treatment in younger age is to rectify the developing dento-alveolar, skeletal and muscular imbalances. With growing dependence on arch development and expansion, the pendulum is oscillating more towards the non-extraction treatment lately, in resolving constriction and crowding issues. Since, a limited number of attempts have been made for mandibular expansion, this study aimes to evaluate the effect of different modes and sites of loading on the expansion of preadolescent mandible using biomechanics.* ***Study design:*** *To address the research purpose, a total of 9 Finite Element models were simulated. Biomechanical response of the mandibular bone and dentition was analyzed under different loading conditions including site and mode, using the simulated FE models.* ***Results:*** *The values of displacement envisaged by the FE models, predict hybrid mode to offer substantial expansion of the mandibular bone as compared to tooth borne and bone borne. In addition, biomechanical effect of site II on mandibular expansion in terms of displacement on X-axis, was significant.* ***Conclusion:*** *In conclusion, the results of our study suggest hybrid mode at site II to be better option for true bony expansion in preadolescent mandible.*

Key words: *Mandibular expansion, stress, strain, displacement, FEA*

INTRODUCTION

Tooth size-arch length discrepancy is considered to be one of the most common forms of malocclusions, experienced in the clinical practice. Clinical characteristics including decreased mandibular arch length, narrow inter-canine width, lower anterior teeth crowding and posterior buccal cross-bite are considered to be associated with transverse mandibular deficiency[1],[2]. The routine treatment plan for mandibular expansion in adolescence is by active or passive expansion. Various non-surgical methods including Schwarz appliance, lingual arch, functional appliance, and archwires have been attempted before. Although these techniques resulted in the expansion of mandibular arch, nevertheless the expansion observed in the previous studies was mainly due to the inclination of teeth, rather than true expansion of the mandibular body. Moreover, disadvantages such as compromised facial aesthetics, and a compromised periodontium caused by excessive dental expansion and proclination, have been noticed for such treatments.

Three-dimensional finite element analysis is a modern research tool for numerical simulation of mechanical processes of a real physical system, that offers several advantages, such as the accurate representation of complex geometries, easy model modification, and representation of the internal state of stress and other mechanical qualities[3]. Besides, it is considered as a valid and a reliable approach for quantitative evaluation of stress-strain and displacement in the dento-alveolar structures[4]. Moreover, it provides us with a freedom to simulate orthodontic force systems applied clinically, in addition

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to evaluation of dento-alveolar response to the mechanical loads in three-dimensional spaces[5].

When bone is subjected to mechanical load, it shows two types of inherent physiological mechanisms 1) bone modeling and 2) bone remodeling[6]-[11]. Physiological characteristic of the bone to adapt to the mechanical environment is a well-known fact[6], and mandibular bone is no exception to this. Hence, it can be contemplated that by changing the loading site accompanied by different modes of force application, the biomechanical response of bone tissue might change and significant mandibular expansion can be achieved. Therefore, we hypothesize that change in the site and mode of force application may have a biomechanical impact on mandibular expansion, which can further contribute substantially to better treatment outcomes. With this intent, the present study was aimed to evaluate the biomechanical response of the mandible, when subjected to different modes and sites of force application by means of Finite Element (FE) method. Although numerous FE studies have been performed to investigate the biomechanics and mechanobiology of mandibular expansion, the novelty of this paper lies in the fact that, it is the first study of its kind comparing different modes and sites of force application for the purpose of expanding a preadolescent mandible using FEA.

MATERIALS AND METHOD

Geometric construction of the FE Model

A CBCT scan projection of a preadolescent mandible was obtained from the Department of Oral and Maxillofacial Radiology. These Computed tomography scans (slice thickness 1 mm, pixel size 0.42 mm), served as the pattern for construction of the mathematical model. Processing of the data was performed using Mimics® software, version 9.0 (Materialise Inc., Leuven, Belgium). The DICOM file (digital imaging and communications in medicine) generated through CBCT evaluation was imported to Mimics software (Materialise) for semi-automatic edge detection, followed by meshing of surface elements using an automated meshing module–Geomagic Studio (Geomagic Company , NC, USA) to construct 3D analytical model of mandible and dentition through thresholding, region growing and calculating 3D operations. With the help of Rapidform software (version 6.5; INUS, Seoul, Korea), we performed Scaling and Boolean operations on the surface model of individual tooth and mandibular bone to produce cortical bone; with an average thickness of 2.0 mm; trabecular bone, with an average thickness of 2mm and PDL, with an average thickness of 0.2 mm, thereby creating parametric solids from 3D scans.

Construction of FE model from Geometric model

The constructed model was then exported to finite element software ANSYS (Swanson Analysis Systems, Houston, TX, USA) which divided the geometric model into finite elements and these elements were connected to adjacent elements by means of nodes, thereby creating a numerical representation of the geometric model. The models were meshed using 10-node quadratic tetrahedral elements (Solid187). Table-1 represents the types and number of elements and nodes. For the purpose of generating the FE model, we assembled the teeth, mucosa, trabecular bone, cortical bone and PDL as shown in Figure 1. Besides the five materials used in this study (teeth, mucosa, trabecular bone, cortical bone, and PDL) were assumed to be linearly elastic, homogeneous and isotropic. The material property of PDL is nonlinear, therefore, piecewise linear mechanical property values describing the non-linear elastic stress-strain behavior of periodontal ligament were used in the present study[12](Figure 2). Moreover, the Preconditioned Conjugate Gradient (PCG) iterative solver strategy was employed in the present study. Subsequently, the simulated FE model behaved like the actual prototype after the allocation of material properties like Young's modulus and Poisson's ratio (lateral strain/longitudinal strain). The Geometric and FE models used in the study are shown in Figure 3 (a and b respectively).

Nine different FE models of a preadolescent mandible including three diverse modes of force application and three different sites were designed and structured in the present study. Each FE model was subjected with a tooth-borne (TB), bone-borne (BB), or a hybrid device (HY), for the prediction of biomechanical response. Biomechanical parameters including stress, strain, and displacement (amount and direction in relation to the X axis) on the tooth (crown and root) and bone, were analyzed for each model. Pure horizontal mechanical loads were applied in all the 9 models as illustrated in Figure 4. The baseline characteristics of study design are listed in Table-2. The study protocol was approved by the Ethics Committee and informed consent was obtained from the subject, before commencing this study.

Figure 1: Illustration of materials (teeth, mucosa, trabecular bone, cortical bone and PDL) that were used to assemble a FEA model.

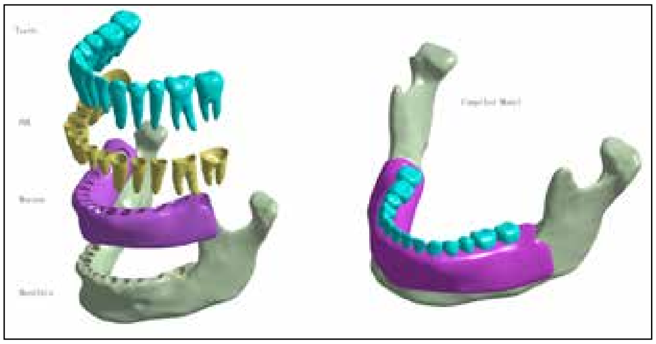

Figure 2: Graph showing non-linear elastic stress-strain behavior of periodontal ligament.

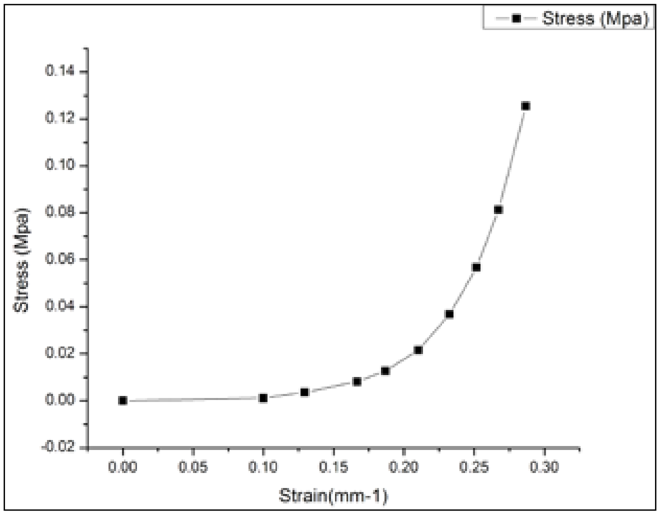

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Table 1: Number of Elements and Nodes

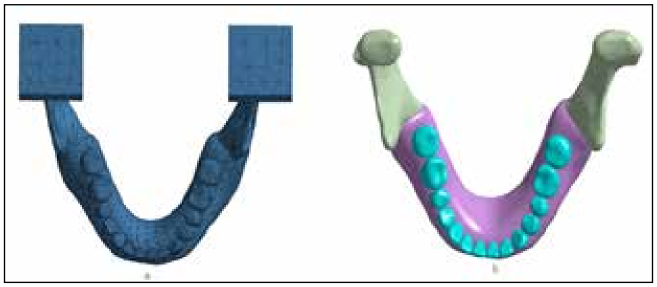
Materials	Elements	Nodes
Cortical bone	15040	28112
Trabecular bone	20735	36206
PDL	35772	72547
Teeth	10636	20375

Table 2 : Baseline Characteristics of Study Design

	Biomechanical Parameter Analyzed	Mode of Load Application	Site of Load Application (I, II, III)*
Part I	STRESS (Crown, Root, Bone)	Tooth Borne	I
			II
			III
		Bone Borne	I
			II
			III
		Hybrid	I
			II
			III
Part II	STRAIN (Crown, Root, Bone)	Tooth Borne	I
			II
			III
		Bone Borne	I
			II
			III
		Hybrid	I
			II
			III
Part III	DISPLACEMENT (Crown, Root, Bone)	Tooth Borne	I
			II
			III
		Bone Borne	I
			II
			III
		Hybrid	I
			II
			III

*Site I – 4, 5, 6 ; Site II –3, 4, 5, 6 ; Site III – 3, 4, 5 (Here 3,4,5,6 represent tooth numbers)

Figure 3: (a) Basic Geometric Model of the mandible; (b) FEA Model of mandible.



RESULTS

In the current simulation, we used 9 different FE models to study the biomechanical effects of different modes and sites of load application on the tooth (crown and root) and bone using a newly defined 3-dimensional coordinate system: X axis; Y axis; Z axis.

Stress

Graphical representation of maximum von Mises stress at various loading sites under different loading conditions is shown in Figure 5. Figure 5(a-c) show that when mandible was subjected to different modes of force application, the magnitude of maximum von Mises stress on the crown was found to be maximum with HY mode at all the loaded sites. On site II and III, there was no change in stress distribution pattern for TB and HY mode as shown in Figure 5(b-c). Likewise, when stress concentration on root was analyzed, TB mode showed maximum stress at all the sites, as demonstrated by the Figure 5(d-f). In addition, Figure 5e shows that at site II, TB and HY mode produced almost equivalent stress on the root. Also, the stress distribution patterns were found to be dissimilar at all the sites. The magnitude of stress concentration shown by BB mode [Figures 5(a-f)] was consistent and minimal at all the three sites. Interestingly, the results of stress distribution pattern on bone were quite different from the above-mentioned results. Here, stress distribution patterns were similar at all the sites. Besides, stress concentration on the bone was maximum with HY mode in all the three sites [Figure 5(g-i)]. BB and TB mode produced almost equivalent stress at all the sites which were maximum at the anterior tooth region [Figure 5(g-i)]. However, a gradual decline in the stress was observed from anterior to posterior tooth region with all the modes and at all the sites. Further, the patterns of stress distribution observed in Figures 5 (b, c, g, h, i) clearly show minimal effect of a change in loading site.

Strain

Likewise, a similar strategy was used to analyze the distribution of strain in the tooth (crown and root) and bone as shown in Figure 6. The graphical depiction of strain distribution in Figure 6 (a-c) shows the pattern of strain produced on the crown when loaded against different modes of force at different sites. It is apparent from the Figure 6 (a and b), when various sites were loaded with different modes, the strain produced on crown was maximum with TB mode at the site I and site II. However, when site III was loaded, HY mode showed maximum strain (Figure 6c). Indeed, a noticeable difference can be observed with the change in load application site. Moreover, the strain produced by BB mode at all the three sites was minimal and comparable [Figure 6 (a-c)]. The strain distribution plot for root revealed a significant rise in strain concentration with TB mode at all the sites as shown in Figures 6 (d-f). Also, the pattern of strain distribution was similar at all the sites with respect to TB and HY mode, however, the amount of strain produced by TB mode was more. Comparatively, TB and HY mode of loading caused more strain concentration on the root when assessed against BB approach which showed almost minimal and equivalent strain at all the sites [Figure 6(d-f)]. Further, notable results were obtained when strain distribution was plotted for bone. Figure 6 (g-i) reveals that the strain concentration on the bone was highest with HY means of force loading at all the three sites when compared with TB and BB. Besides, all the modes displayed a consistent drop in strain concentration on the bone from anterior to the posterior region at all the three sites [Figure 6(g-i)]. In the end, a substantial effect of site and mode on teeth (crown and root) can be observed from the above-mentioned results.

Displacement

Considering the influence of different sites and modes of load application on displacement, we analyzed the displacement of the tooth (crown and root) and bone on X-axis (Figure 7). Figure 7 (a and b) depicts a constant rise in the displacement of the crown from canine to the first molar region at sites I and II, with BB mode of load application. However, a sharp displacement of the crown was noted from canine to first premolar region followed by equivalent displacement posteriorly, when subjected to TB and HY mode as shown in Figure 7 (a). Besides, TB and HY mode showed similar displacement of the crown at site II and III, as in Figure 7 (b and c). Thus, emphasizing the effect of a change in site with different modes of load application. Interestingly, the pattern of root displacement was almost similar for HY and BB modes at all the sites [Figure 7 (d-f)]. However, the amount of displacement produced by HY mode was maximum when compared with TB and BB mode. Further, when the displacement of bone was analyzed, maximum displacement was observed with HY mode at site II and III (Figure 7 h,i). As evident from the Figure 7 (g), TB showed dramatic rise at first premolar, followed by a sharp slump and subsequently an equivalent displacement posteriorly. However, HY and BB mode showed similar patterns of bone displacement at the site I and site II, exhibiting a constant increase in displacement of bone from canine to first molar region (Figure 7 h, i). Furthermore, the response curves showed contrasting patterns between different modes at site III, wherein maximum bone displacement was observed with HY mode. Consequently, displacement of bone on X-axis has shown some promising results with HY mode of load application. The displacements shown by different loading modes at second premolar level obtained from 3D FEM are shown in Figure 8.

Figure 4: Allocation of different loading conditions on FE model. Green colored area on the lingual aspect of all the models represent site of load application while the arrows (yellow colored) represent different modes of load application. Figure 4 (a, b, c) represent different modes of loading (TB, BB, and HY respectively) at Site – I (tooth numbers 4,5,6). Figure 4 (d, e, f) represent different modes of loading (TB, BB, and HY respectively) at Site – II (tooth numbers 3,4,5,6). Figure 4 (g, h, i) represent different modes of loading (TB, BB, and HY respectively) at Site – III (tooth numbers 3,4,5).

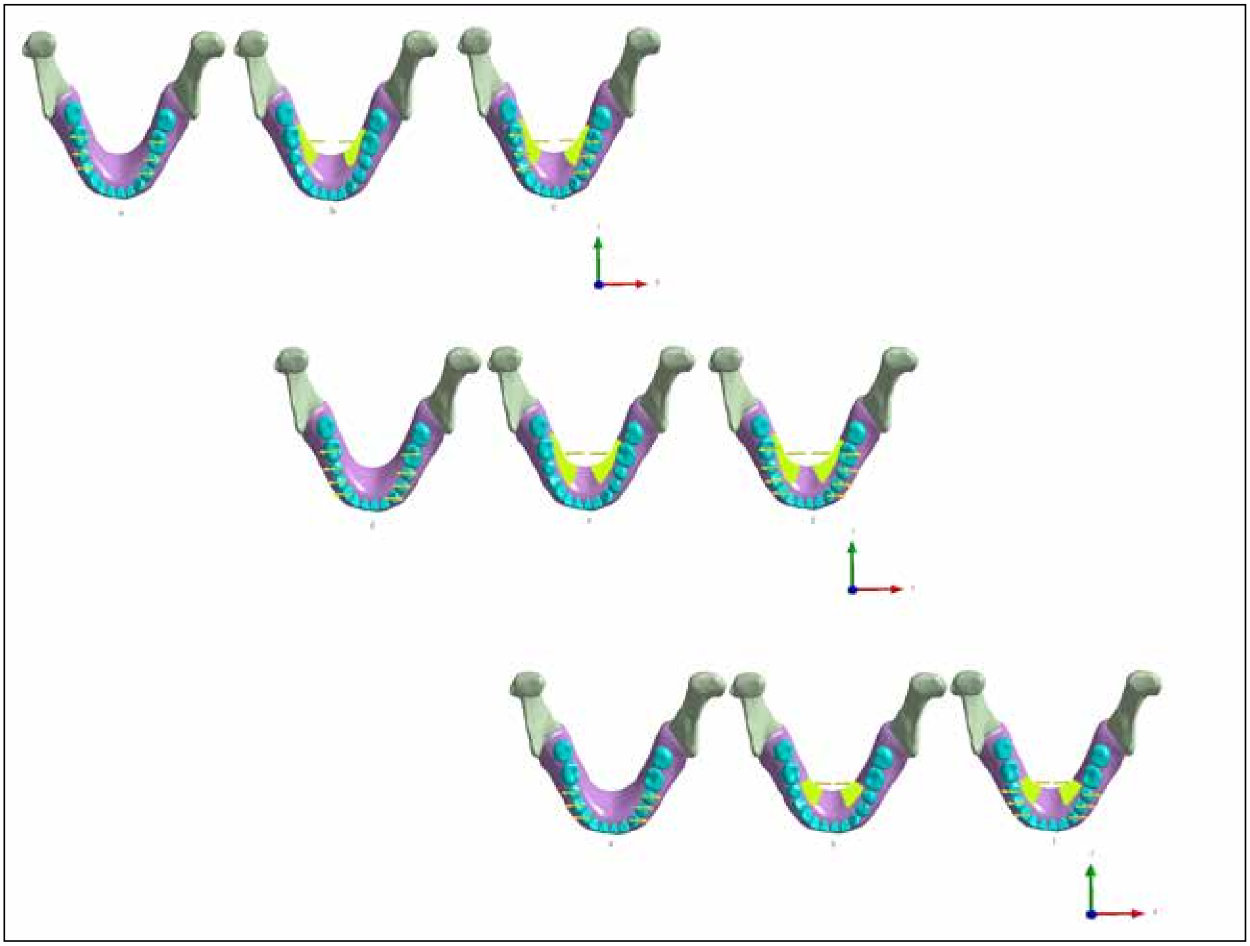


Figure 5: Graphical representation of maximum von Mises stress at various loading sites under different loading conditions. Figure 5 (a,b,c) shows distribution of Maximum von Mises stress on crown at different sites (I, II ,and III respectively) and under different loading modes. Figure 5 (d,e,f) shows distribution of Maximum von Mises stress on root at different sites (I, II ,and III respectively) and under different loading modes.

Figure 5 (g,h,i) shows distribution of Maximum von Mises stress on bone at different sites (I, II ,and III respectively) and under different loading modes.

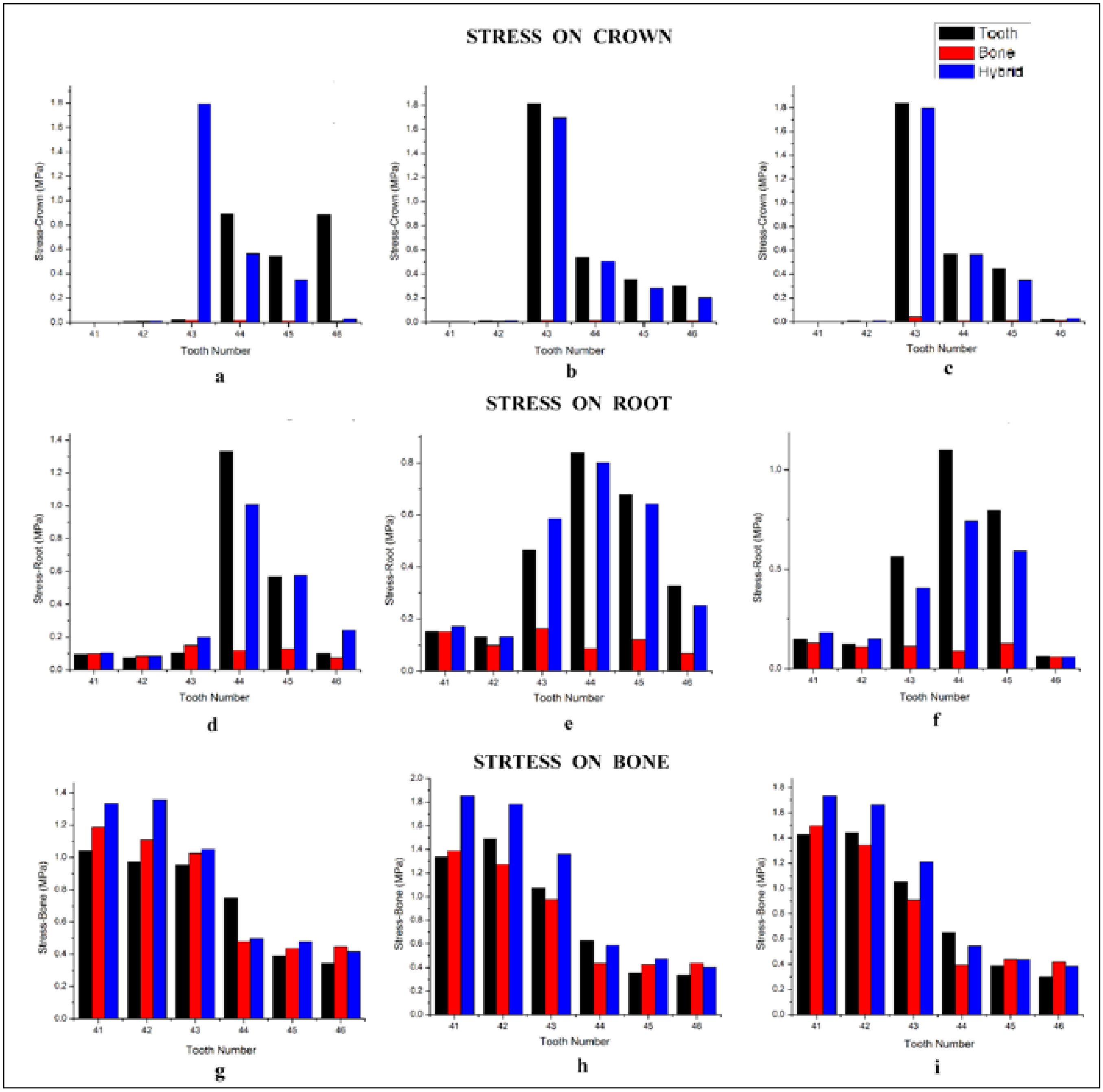


Figure 6: Graphical depiction of strain distribution under different loading conditions.

Figure 6 (a,b,c) shows Strain distribution on crown with respect to different sites (I, II ,and III respectively) and under different loading modes.

Figure 6 (d,e,f) shows Strain distribution on root with respect to different sites (I, II ,and III respectively) and under different loading modes.

Figure 6 (g,h,i) shows Strain distribution on bone with respect to different sites (I, II ,and III respectively) and under different loading modes.

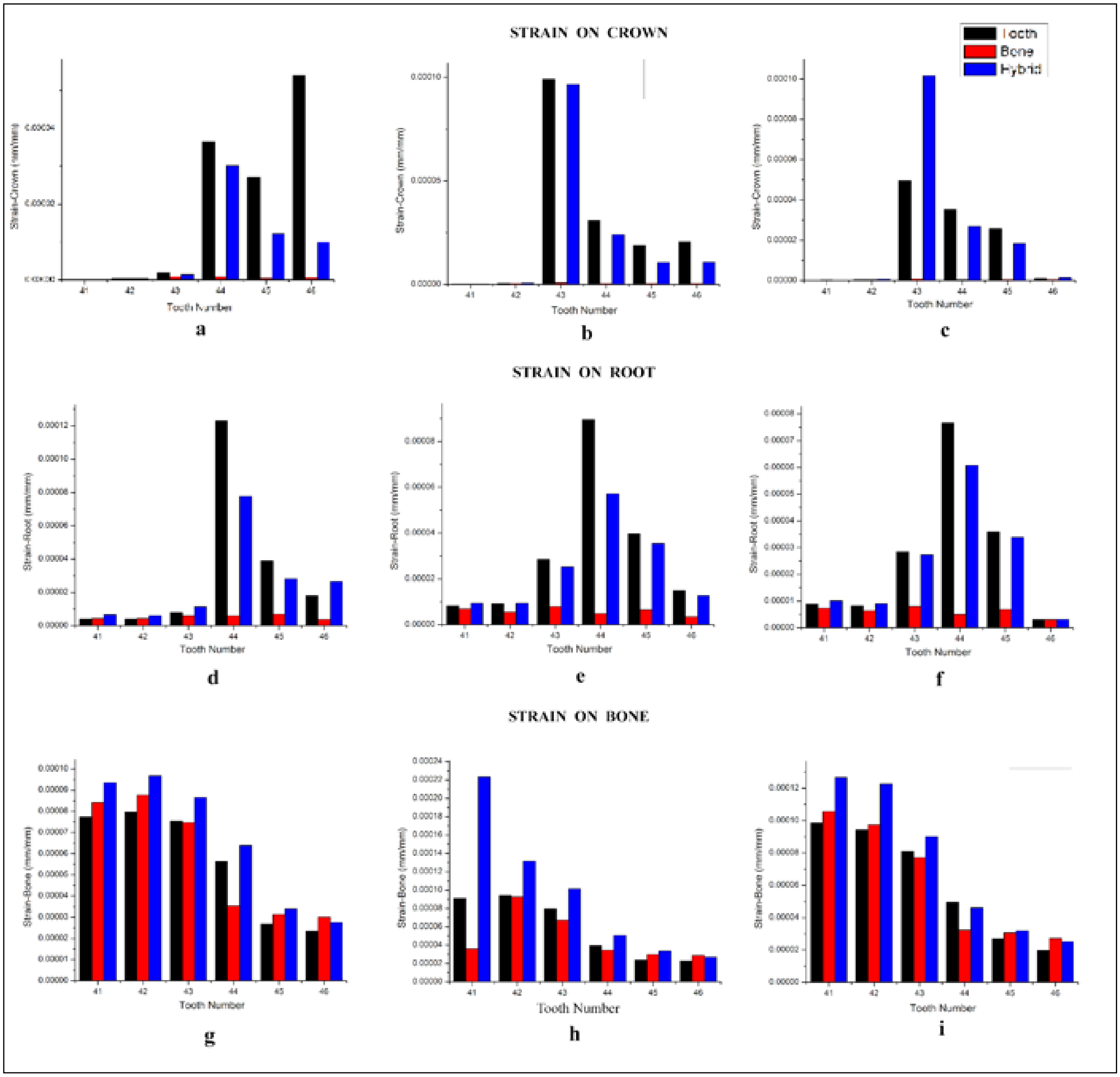


Figure 7 : Response curves showing Total Displacement on X axis with respect to different sites (I, II ,and III respectively) under different loading conditions.

Figure 7 (a,b,c) shows Total displacement of crown at site I, II ,and III respectively, under different loading modes .

Figure 7 (d,e,f) shows Total displacement of root at site I, II ,and III respectively, under different loading modes .

Figure 7 (g,h,i) shows Total displacement of bone at site I, II ,and III respectively, under different loading modes .

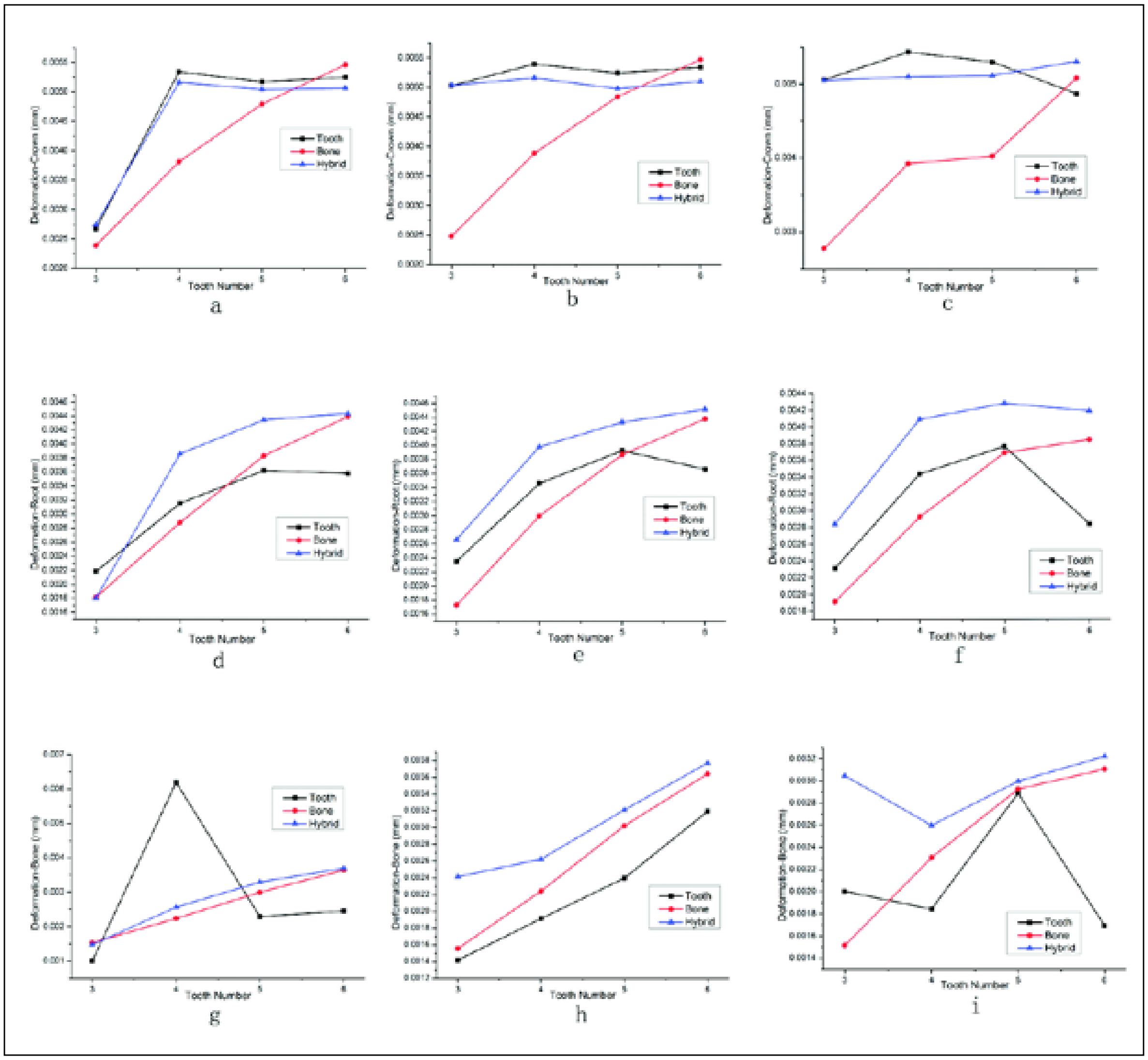
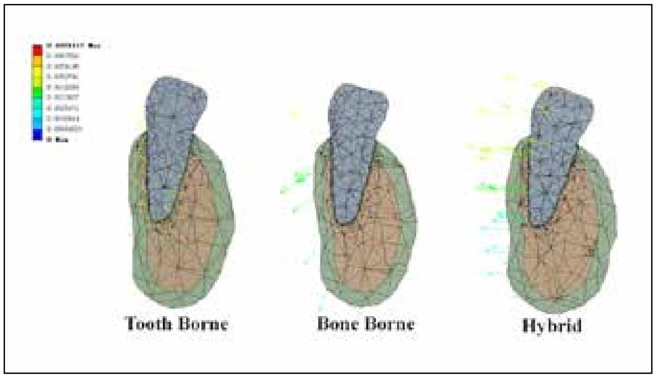


Figure 8 : Displacements vectors for different loading modes at second premolar level obtained from 3D FEM. The predicted expansion of mandibular bone can be well appreciated from direction of displacement vectors in HY mode of loading.



DISCUSSION

Although extraction/ non-extraction arguments in orthodontics have continued over a long period, during the past decade there has been a renewed interest in providing routine relief of crowding without premolar extractions. In this regard, arch expansion can be achieved to solve crowding issues and space deficiency problems without the need for extraction or complicated surgical procedures.

In current mechanotherapy, Rapid Maxillary Expansion is considered as a routine clinical treatment for patients with constricted maxillary arch[13]. This is because the Rapid Maxillary Expansion increases the transverse dimension of the maxillary arch by splitting of mid-palatal sutures[14-17] .In contrast, expansion of mandibular bone becomes difficult, due to the absence of natural bone sutures. Hence, as compared to maxilla transverse mandibular expansion has received little attention of researchers and relatively few studies have addressed true non-surgical mandibular expansion. Indeed, clinicians have been skeptical towards attempting a true mandibular expansion. The results of previous FE studies have provided useful insights towards the prediction of the changes in the dento-alveolar structures followed by the application of load, which formed the basis of the current study. Therefore, the present study intended to evaluate the biomechanical effects of different modes and sites of load application on dentoalveolar structures, to come out with the most pertinent site and mode of load application, for the purpose of true mandibular expansion by non-surgical means in pre-adolescent patients.

In recent years, an increasing tendency of constricted mandibular arch patients favoring conservative treatment over tooth extraction has led to a review of the various treatment modalities, including 1) Active expansion using different appliances to push the teeth into wider arch and 2) Passive expansion using Lip Bumpers, Vestibular Screens etc [18].Greenfield *et al* [19] in their study reported significant expansion of mandible using a lip bumper and multibracket appliance. Likewise, expansion of the mandibular arch using Schwartz removable appliance was reported by Sekizaki *et al* [20]. Likewise, Kiyoshi Tai *et al* [21] reported the use of Schwartz appliance for the purpose of mandibular expansion and results of their study were in agreement with those of the previous studies. Similarly, the biomechanical study by Motyoshi[17] reported mandibular lateral expansion resulting due to labial rotation of the teeth. Kenshi Maki *et al* [22] also documented similar results using Bi helix appliance. Moreover, the results of FEA study by Baswaraj *et al* [5] also show an increase in arch width and perimeter associated with mandibular expansion. However, expansion of the mandibular arch reported in the previous studies was mostly due to tipping of the molars and partly by bodily movement. On the contrary, recent findings have indicated promising results as suggested by Hamada *et al* [23] in their animal study. They have reported changes in the alveolar process with mandibular expansion in beagles. Furthermore, Boccaccio *et al* [24] performed an FEA study on adult mandible with different devices (tooth-borne, bone-borne, and hybrid) using surgical approach and assessed the reliability of distractor in transferring expansion to the mandibular bone. In the present study, we also analyzed different devices for the purpose of mandibular expansion using FEA. However, the novelty of this study lies in the fact it is based on a nonsurgical approach for the preadolescent mandible, and in addition to different modes, we also assessed different sites in the present study.

In the present study, the values of displacement of bone predicted by the FE model increased from the anterior towards the posterior tooth region (Figure 6h), which was in contrast to the findings of Basciftci *et al* [25], and Boccaccio [24] who observed greatest widening at the symphyseal region in their study, and suggested that the widening effect gradually diminishes from the anterior to the posterior. Also, the expansion predicted for mandibular arch appears to be more significant with HY and BB modes, as compared to TB mode. In particular, HY mode was found to be the best mode of force application [Figure 6(h and i)] presumably due to the fact that, the fixation points for hybrid mode are located both on the basal bone and on the teeth. That is to say, the points located on the teeth allow controlled displacement while the fixation points located on the basal bone permit reduction in the parasitic rotations produced by the masticatory muscles. In addition, the displacement vectors shown in Figure 7 also predict HY mode to provide a substantial expansion of the mandibular bone. Besides, although the absolute values differed, the response curves showed similar tendencies with respect to change in site, except Figure 6 (h), which clearly signifies an obvious and consistent increase in mandibular body expansion from anterior to posterior. Consequently, the findings of our study suggest that loading at site II is a better choice when compared to site I and III.

One of the most critical factors to be considered for a mandibular expansion study like ours is stability. In contrast to maxillary expansion, mandibular expansion has not been generally accepted as a viable treatment due to the fact that any increase in mandibular intercanine width is subject to relapse[26],[27]. Firstly, a possible explanation to post-treatment instability could be the pressures exerted by lips and cheeks, as suggested by Shellhart *et al* [28] from their experimental study. However, they concluded that labial soft tissues get adapted with the decrease in pressures gradually. Besides, Boccaccio et al also suggested that parasitic rotations generated by the masticatory muscles become less significant over time, resulting in greater stability. Secondly, most recent follow-up studies have confirmed that expansion of mandibular interpremolar and intermolar dimensions to be more stable than intercanine expansion. In this regard, Gardner and Chaconas[29] investigated the stability of mandibular arch dimensional changes of 103 cases and concluded that significant expansion of intermolar widths could be stable in non-extraction cases. A recent study by Fidan et al also shows an increase in mandibular arch perimeter by 7.4 mm brought about by Trombone appliances which cause labiolingual and transversal expansion of the mandibular arch[30]. Likewise, Handelman[31] and O'Grady *et al* [32] in their respective studies demonstrated the concurrent expansion of both arches with stable long-term outcomes. Also, Brust and McNamara[33] in their large sample study noted a clinically relevant increase in both arch perimeter and the transverse dimension. Therefore, it can be suggested that, despite, initial instability caused by the labial soft tissues and masticatory muscles, stable outcomes might be achieved gradually due to the adaptive behavior of muscles and soft tissues.

Another significant aspect that needs consideration for an FEA study like this, is bone remodeling. Bone remodeling is a multifactorial process which is dependent on both mechanical and biological factors. Mechanical factors are related to the new distribution of loads caused by the site of appliance placement, physical characteristics of the appliance (design), and type of anchorage (TB, BB or HY). Biologics are related to age, the weight of the individual, and initial bone mass. Considering the role of biological factors in bone remodeling, preadolescent mandible was used in the current study which has significant potential for bone remodeling. Bone is a dynamic tissue that is tightly regulated by a multitude of homeostatic control and constantly remodels itself to more efficiently endure external forces[34],[35]. One key environmental regulator of bone is mechanical stimulation. Wolff's law recognizes the response of bone to mechanical stimulation and states that as a consequence of continuous loading, bone changes its internal architecture according to mathematical rules and, as a secondary effect and governed by the same mathematical rules, also changes it shape[10]. This alteration of the normal biomechanics results in a phenomenon called adaptive bone remodeling, which is nothing but physiological remodeling occurring in a new biomechanical environment[36]. The above-mentioned theories of bone remodeling have been used successfully in conjunction with the FEM to predict density and bone adaptation. From the biomechanical point of view, bone is considered to be time-dependent or viscoelastic material because of the fact that stress-strain characteristics and strength properties of the bone are dependent on the applied strain rate. In addition, the bone's stress-strain response depends on the load's direction; the bone's geometry, microarchitecture, and density; and the influence of surrounding muscular contractions, thereby suggesting bone to be an anisotropic material. Besides, the muscles attached to the surface of compact bones can also significantly influence the intensity of a load[37], which might contribute to the change in biomechanical properties of bone. A similar response with respect to biomechanical parameters was observed in the present study when site and modes of load application were changed. Although some amount of remodeling does take place at the site of force application, the amount of bone remodeling was not evaluated in the present study, since, the authors of the present study are clinicians and the implementation of extendable numerical algorithm to build up the remodeling process of bone due to mechanical stimulus was beyond the scope of this study.

Limitations

The strengths of this study include a comprehensive finite element analysis on a preadolescent mandible, and employing extracted data for the assessment of potential mandibular bone expansion. However, some limitations should be considered in our study. First, Finite Element Analysis is mathematical in vitro study that may not simulate the clinical situation completely. For the creation of the finite element models, the materials used in this study were assumed to be isotropic homogeneous. Therefore, the resultant stress values obtained may not be accurate quantitatively but are generally accepted qualitatively. Second, some bone remodeling does take place at the site of force application. However, considering the implementation of a mathematical algorithm to be beyond the scope of this paper, bone remodeling algorithm was not developed. Finally, our study is constrained to biomechanical factors, and no animal experiments have been performed yet. Due to the limitation pertaining to the study, further research regarding Three-dimensional Finite Element Analysis combined with experimental studies and long-term clinical evaluation is required to quantitatively validate our numerical results.

CONCLUSION

Within the limitations of this study, the data from our study may provide a valuable reference for future clinical and experimental studies concluding that Hybrid mode of force application when loaded at site II, might offer considerable expansion in the preadolescent mandible. Consequently, even though significant insights have been gained in the field of mandibular expansion, further avenues of research are needed to clarify the role of mandibular expansion stability for more substantiated results.

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