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Comparative Evaluation of LED Light Application and Heat Generation with Three Different Wavelengths of Frequency on Soft Tissues in Bringing Faster Orthodontic Tooth Movement: A Finite Element Model Study

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ABSTRACT

Background: The duration of orthodontic treatment is often a significant deterrent for patients when considering conventional mechanics, which can be time-consuming. Photobiomodulation (PBM) utilizes visible red to near-infrared wavelengths of light frequencies to expedite orthodontic treatment time.

Objective: To investigate the effect of three Light Emitting Diode (LED) frequencies and their heat generation on soft tissues in accelerating tooth movement through Finite Element Method (FEM) study.

Material and Methods: In this FEM study, a three-dimensional FEM model of the skull of a male patient with mild to moderate crowding in the maxilla, and mandible. The dentitions were scanned using a Computed Tomography (CT). A static force of 70 gm on the anterior region of the maxilla and mandible was applied from the labial sides, and a second static analysis was carried out by using both a 70 gm of force and thermal load with three different frequencies of 740, 850, and 940 nm on the 1st and 3rd quadrants. The effect of LED application and heat generation was assessed on soft tissues in bringing faster orthodontic tooth movement.

Results: Increased tooth movement with combined loading case in the 1st and 3rd quadrants when compared with the 2nd and 4th quadrants. The temperature distribution was higher at 940 nm followed by 740 & 850 nm of frequency.

Conclusion: Faster movements were observed in the combined loading case in the 1st and 3rd quadrants compared to static loading in other quadrants. Heat generation was higher with 940 nm frequency followed by 740 and 850 nm.

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Keywords

Computed Tomography; Finite Element Analysis; Light Emitting Diode; Photobiomodulation Therapy; Maxilla; Mandible

Introduction

The lengthy duration of orthodontic treatment, typically ranging from 12 to 24 months or even longer, is often the primary disincentive for patients to accept conventional mechanics [1]. The significant drawback of longer treatment duration has led to patients discontinuing orthodontic treatment midway. In attempts to expedite orthodontic tooth movement, various procedures, such as surgical and

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pharmacological methods have been utilized, but these invasive approaches often result in patient discomfort, including pain, swelling, and side effects [2].

Photobiomodulation (PBM) therapy, Low-Level Light Therapy (LLLT), or Light Accelerated Orthodontics (LAO) [3], is a recently developed noninvasive procedure in the field of orthodontics. It utilizes light energy in the form of visible red to near-infrared wavelengths (600-1000 nm) to induce changes in cellular biology, resulting in bone remodeling and acceleration of orthodontic tooth movement. This innovative approach aims to secure treatment duration and reduce overall treatment time [4]. A literature search has divulged that fewer studies have been conducted on PBM to accelerate tooth movement, and few studies were on animals [5-7].

Understanding the response of oral soft tissues to various photobiomodulation parameters, such as frequencies, energy density, power output, and heat generated, is crucial. The stomatognathic system investigates using computational techniques, leading to a comprehensive evaluation before implementing photobiomodulation as a method to accelerate tooth movement in conjunction with orthodontic treatment [8].

Finite Element Analysis (FEA), developed by engineers in the 1950s, has found extensive applications for various fields and is considered a fundamental method to determine stress and deformations in complex structures with different geometries. Further, FEA influences concrete information and insights into various aspects of the analyzed structures [9].

The current trend in orthodontics emphasizes an evidence-based approach, leading to treatment planning based on scientific rationale and considering soft tissue responses. The introduction of modern technology has revolutionized the execution of composite and risky procedures, resulting in their safe and reliable implementation. Furthermore, these advancements cause accurate simulation, providing a valuable tool for orthodontic treatment planning [10]. In orthodontics, Finite-Element Method (FEM) has been used to study stress-strain distribution, bone loss, and root resorption during tooth movement [11-14].

The literature currently provides limited information on the application of Light Emitting Diode (LED) lights and the associated heat generation on soft tissues to accelerate tooth movement. Therefore, FEM study was conducted to investigate the effects of LED light application and heat generation using three different wavelengths (740 nm, 850 nm, and 940 nm) on soft tissues to improve orthodontic tooth movement.

Material and Methods

This work utilized FEM to examine a computed tomography (CT) scan of the complete cranial structure of a 20-year-old male individual presenting mild to moderate crowding in the upper and lower anterior areas. The CT scan images were acquired with an X-force/SH spiral CT scanning device (Carestream France version Cs 9300).

The acquired images were subsequently transformed into Dicom data to generate a geometric model, via Materialise's Interactive Medical Image Control System (MIMICS 8.11). The data obtained from mimics, which consisted of cloud data points and lines, was afterward converted into Standard Triangle Language (STL) format. The regions of interest, such as the jaw, maxilla, teeth, and bones, were isolated.

The data acquired by mimic's software was subsequently integrated into Rapid Form software, facilitating the conversion of cloud data points into surface representations. The surfaces with underwent conversion were subsequently stored within the Initial Graphics Exchange Specification (IGES) geometric model, which exclusively included surface data. The bones, mandible, teeth, maxilla, PDL (periodontal ligament), and sutures were imported as geometric models into the meshing software "Hypermesh 2019.0" (Altair Hyper works). This software was utilized to turn the geometric models into finite element models. In the Hypermesh software, the discrete representation (mesh) of various components, such as brackets, bones, sutures, teeth, and periodontal ligament (PDL) was afterward generated and combined. The final finite element model (Figure 1) comprised of nodes and element data was presented as a meshed model.

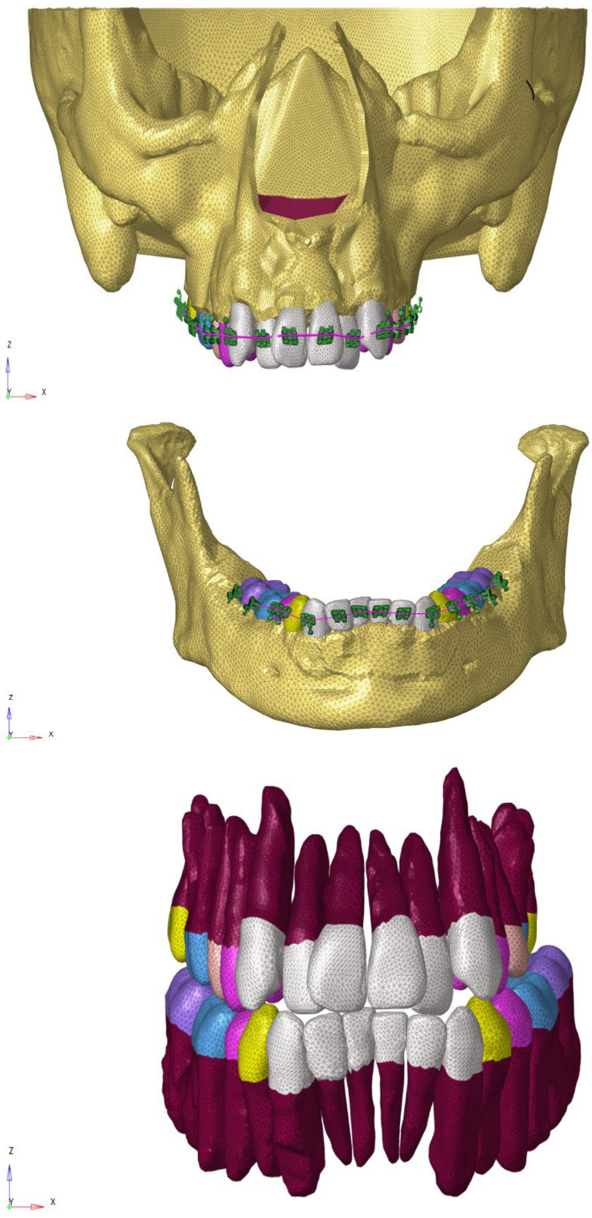

Figure 1: Hypermeshed model of skull with maxilla, mandible and dentitions

The finite element analysis was conducted on a workstation computer equipped with an Intel Core 2 Duo processor operating at a frequency of 2.1 GHz and 2 GB of RAM. The finite element model was constructed using three-dimensional tetrahedral components. This study utilized a total of 753,505 tetrahedral elements and 159,285 nodes. The finite element model was assigned with boundary conditions, loads, and material attributes. Table 1 presents the material parameters of the skull, suture, bone, teeth, and PDL.

The FEM model was partitioned into four quadrants, specifically for the maxilla and mandible. The first and second quadrants were located in the maxilla, while the third and fourth quadrants were situated in the mandible. The first and third quadrants were designated for experimental purposes, whereas the second and fourth quadrants were designated for nonexperimental purposes. Both conventional and thermal loads were utilized. The observed tooth displacement was recorded along various axes: X denoting lateral movement, Y representing anteroposterior displacement, with +Y indicating posterior movement, and -Y indicating anterior movement. Additionally, +Z indicated intrusion in the maxilla, while -Z indicated extrusion in the maxilla. In the context of the mandible, the positive direction along the Z-axis represents extrusion, whereas

Table 1: Material properties used for FEA (Finite element method) study

Part	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	13,700	0.3
Cancellous bone	1,370	0.3
Suture	10	0.49
PDL	0.069	0.49
Tooth	20,700	0.3

the negative direction along the Z-axis corresponds to intrusion.

The present study employed a static structural analysis utilizing conventional sliding mechanics with labial brackets. A 0.022-inch slot and a 0.014 niti arch wire were utilized, along with a 70-gm activation load. This analysis was conducted on the maxillary and mandibular teeth in all four quadrants. The primary focus was on measuring the movements of the anterior teeth, specifically from canine to canine, in three dimensions: X (lateral), Y (anterior-posterior), and Z (vertical) directions.

A subsequent transient thermal study was conducted on the model, wherein LED lights emitting at frequencies of 740, 850, and 940 nm were applied for a duration of 180 seconds in the central, lateral, and canine regions of the 1st and 3rd quadrants. The objective of this analysis was to determine the temperature distribution in the FEM mode. Subsequently, a comprehensive thermo-mechanical analysis was conducted, incorporating a mechanical load of 70 grams and a thermal load characterized by the distribution of temperatures induced by LED lights emitting at frequencies of 740, 850, and 940 nm. The duration of this thermal load application was set at 180 seconds, targeting the central, lateral, and canine areas. The measurements of anterior movements were conducted in the first and third quadrants along the X, Y, and Z axes. Figure 2 illustrates the representation of static and coupled thermal-mechanical loading.

The selection of a 70-gram force was based on the established range of forces recommended for various orthodontic procedures. According to Proffit et al. (2019. Contemporary Orthodontics. 6th ed. Amsterdam: Elsevier; p. 256), optimal forces for tipping, intrusion, extrusion, and rotation correction often ranges from 35 to 60 gm, while body movement necessitates forces between 70 and 120 gm. The study involved a comparison of applied loads to assess the effects resulting from mechanical and thermal loading. This analysis was conducted using ANSYS software version 17.2 in accordance with the imposed loads and boundary constraints. Following the completion of data processing, a comprehensive documenting of the obtained results was undertaken, followed by a thorough interpretation of these results.

Results

The results of the present study indicate that there was increased tooth movement observed in the static structural analysis when subjected to mechanical loading in both the Z and Y directions across all four quadrants. The applied load consisted of a force of 70 gm, and frequencies of 740, 850, and 940 nm were used

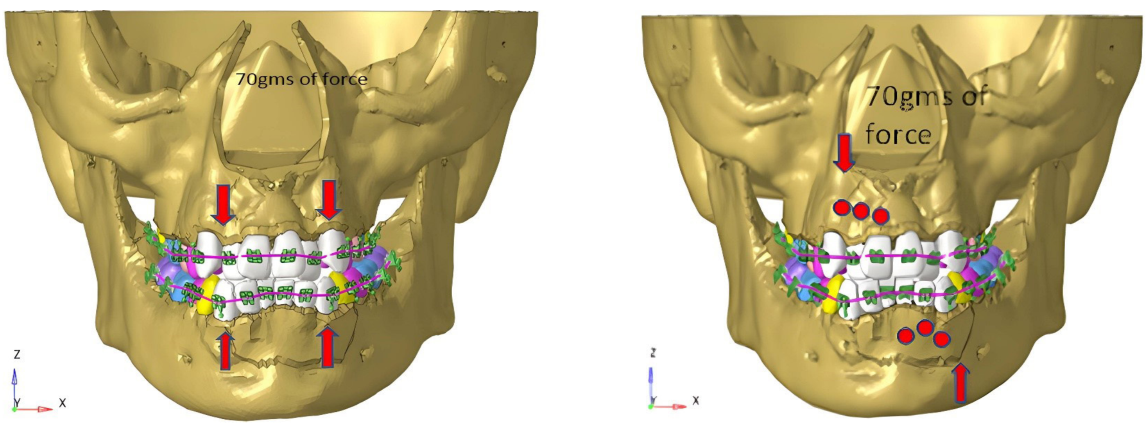

Figure 2: Applied load and boundary condition for static and combined thermal mechanical load.

during the simulation (Figures 3-5).

In the course of conducting the transient thermal analysis, the temperature distribution and heat generation at the 180-second mark exhibited distinct variations across all three frequencies. At a wavelength of 740 nm, the temperature measurements at the central incisor, lateral incisor, and canine in the first quadrant were 100.07° F, 99.68° F, and 99.59° F, respectively. In the third quadrant, the temperature measurements were 101.83° F, 102.90° F, and 102.73° F for the central incisor, lateral incisor, and canine, respectively.

The temperature readings at the central incisor, lateral incisor, and canine teeth in the first quadrant were 99.028° F, 98.779° F, and 98.789° F, respectively, when measured at a wavelength of 850 nm. In the third quadrant, the temperature readings at the central, lateral, and canine teeth were 99.916° F, 100.453° F, and 100.369° F, respectively.

At a wavelength of 940 nm, the temperature measurements were obtained as follows: 101.853° F at the central incisor, 100.921° F at the lateral incisor, and 100.959° F at the canine tooth in the first quadrant. In the third quadrant, the temperature measurements were 105.184° F at the central incisor, 107.197° F at the lateral incisor, and 106.884° F at the canine tooth. The rationale for this comparison can be ascribed to the use of distinct characteristics, such as energy density and power output, within the scope of this investigation. The thermal analysis findings are depicted in Figure 6.

In contrast, the examination of the integrated thermal-mechanical static analysis involving all three frequencies revealed greater tooth displacements in the negative Y and negative Z directions inside the first and third quadrants (Figures 7-9). The analysis of the displacement contours was subsequently conducted for all three frequencies. The parameters utilized are presented in Table 2, while the variations, outcomes, and deductions from static structural and coupled thermal-mechanical analyses for all frequencies are displayed in Figure 10.

The findings indicated that there was a greater degree of tooth movement observed in the 1st and 3rd quadrants when thermal-mechanical loading was applied in combination, as opposed to the 2nd and 4th quadrants. Elevated displacements were noted in both the buccolingual and vertical orientations. The study observed heat generation and temperature distribution at wavelengths of 940 nm, 740 nm, and 850 nm, respectively.

Discussion

The process of orthodontic tooth movement involves the application of force, which triggers bone remodeling at the molecular and cellular levels within the periodontium. The duration and time required for orthodontic treatment are of paramount significance to patients. One potential approach to decreasing the duration of orthodontic therapy is the acceleration of tooth movement. The utilization of light to expedite orthodontic treatment has been a well-established practice within the field of orthodontics. The therapeutic approach referred to as PBM or LLLT involves the utilization of LED lights to administer incoherent light. This form of light is nearly monochromatic in nature and possesses several advantageous characteristics, including its lack of side effects, ease of use, affordability, and noninvasive nature [3].

The PBM exerts its effects on cellular tissues by targeting the mitochondria, specifically the mitochondria within the cell, leading to an increase in mitochondrial metabolism, which is facilitated by a terminal enzyme known as Cytochrome C Oxidase (CCO) in the respiratory chain within the cell. Consequently, a series of signaling pathways is activated, ultimately leading to bone turnover and resulting in accelerated tooth movement.

The literature review reveals a lack of information regarding heat generation and temperature distribution during photo-biomodulation therapy in the research conducted on the use

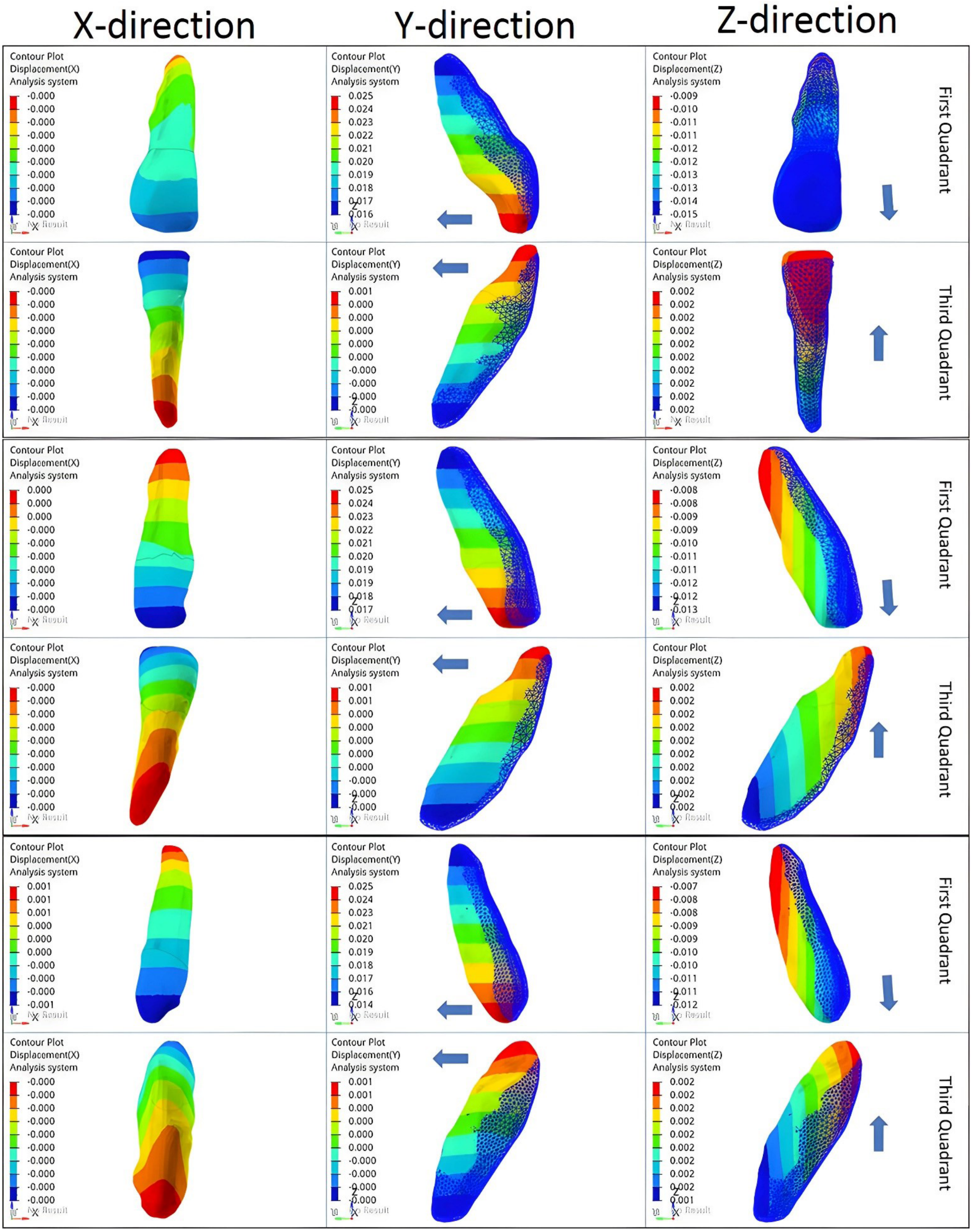

Figure 3: Movement in central, lateral and canine teeth with static structural analysis with only mechanical loading in first and third quadrant at 740 nm frequency and arrow representing the direction of movement.

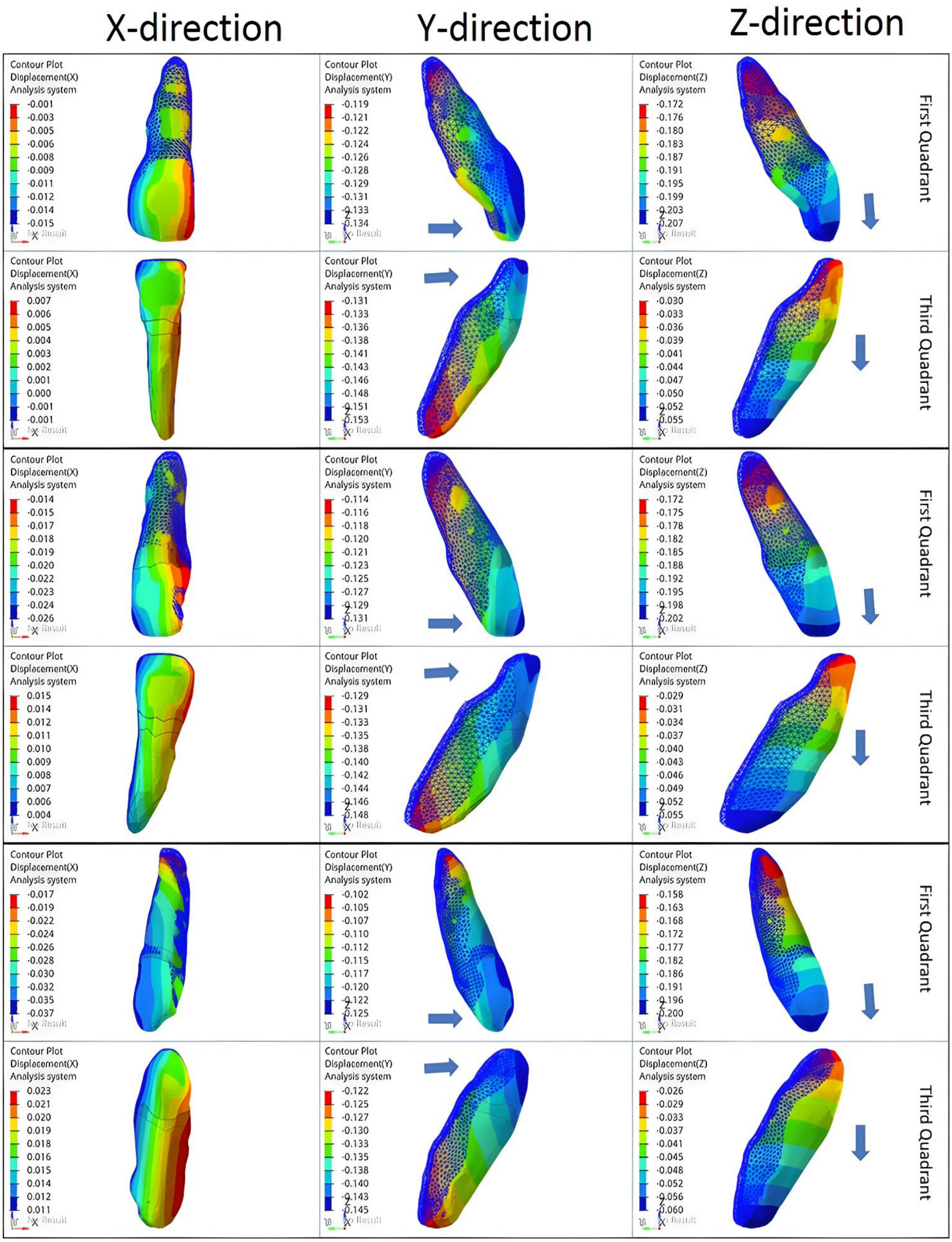

Figure 4: Movement in central, lateral and canine teeth with static structural analysis with only mechanical loading in first and third quadrant at 850 nm frequency and the arrow representing the direction of movement.

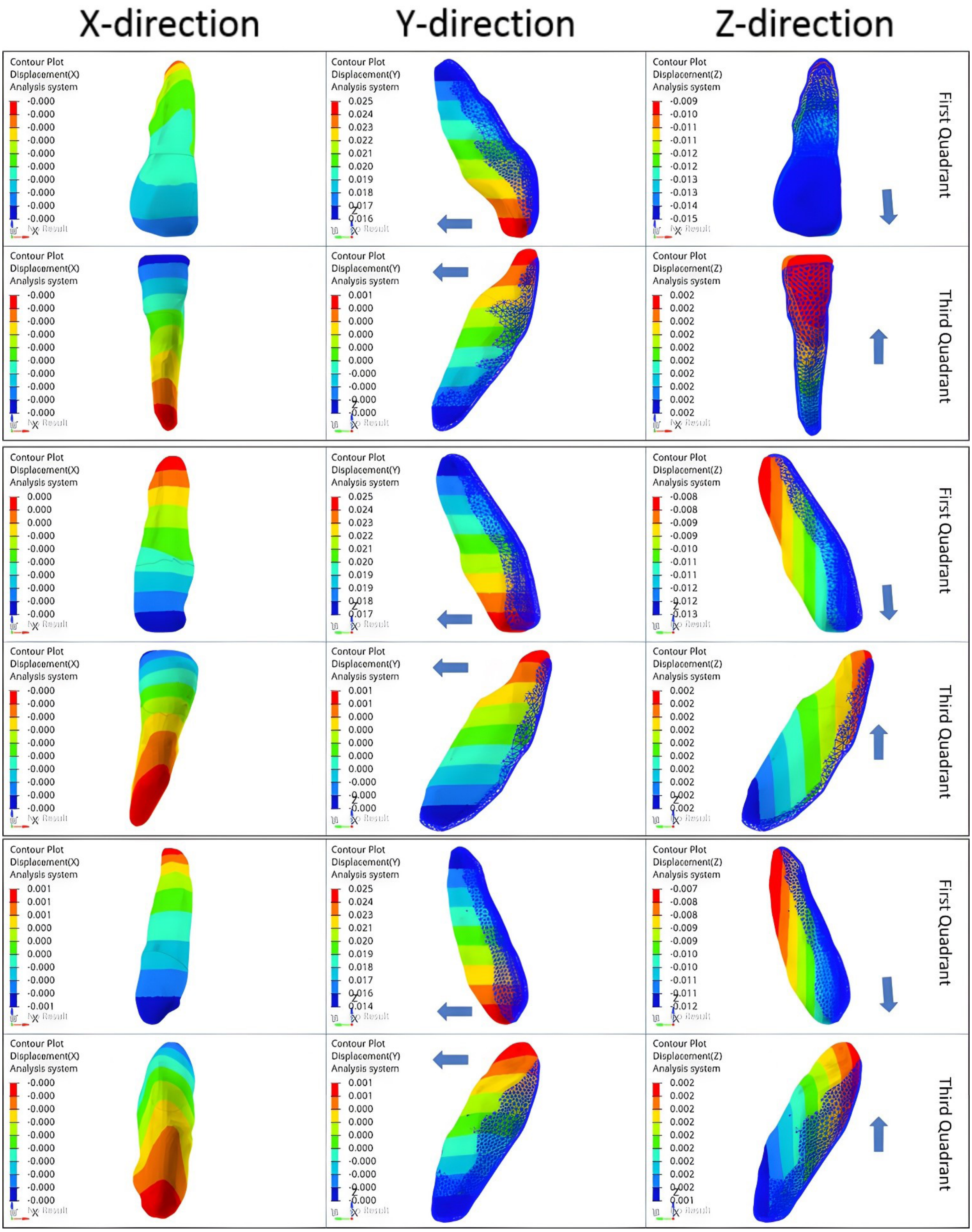

Figure 5: Movement in central, lateral and canine teeth with static structural analysis with only mechanical loading in first and third quadrant at 940 nm frequency and the arrow representing the direction of movement.

of photo biomodulation therapy to speed up tooth movement. Understanding the reaction of oral soft tissues to various parameters of photo biomodulation, such as frequencies, energy density, power output, and heat generation, is significant. This understanding can be achieved through a systematic examination of the stomatognathic system, which is complex in nature. In the field of orthodontics, computational techniques can investigate these parameters before utilizing them to expedite tooth movement [7].

The field of craniofacial orthodontics necessitates a comprehensive comprehension of the intricate nature of stress and strain, as well as the force vectors, that are implicated

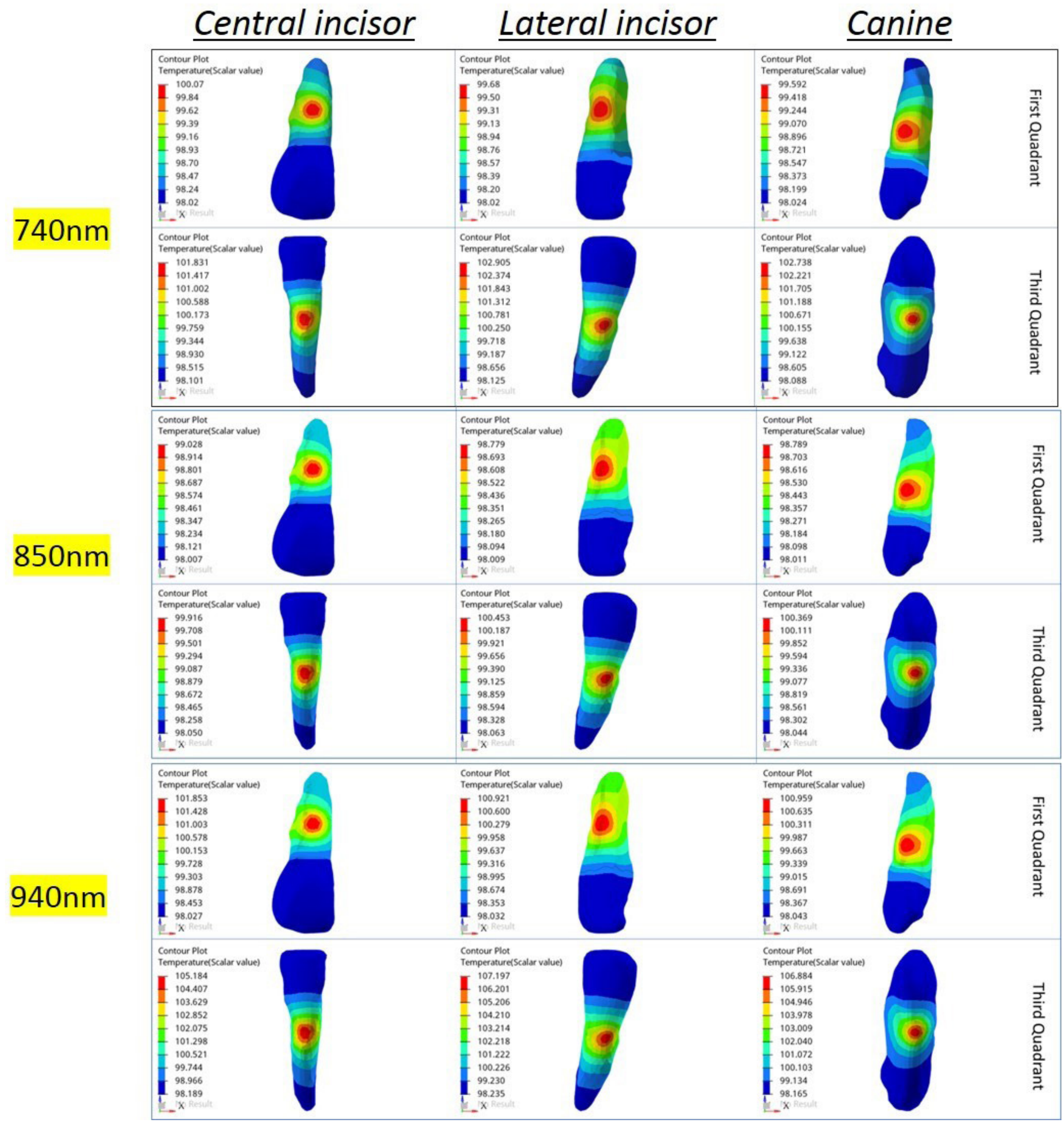

Figure 6: Temperature distribution at 180 sec in degree farhenit with 740,850 & 940 nm frequency at central, lateral and canine tooth in first and third quadrant.

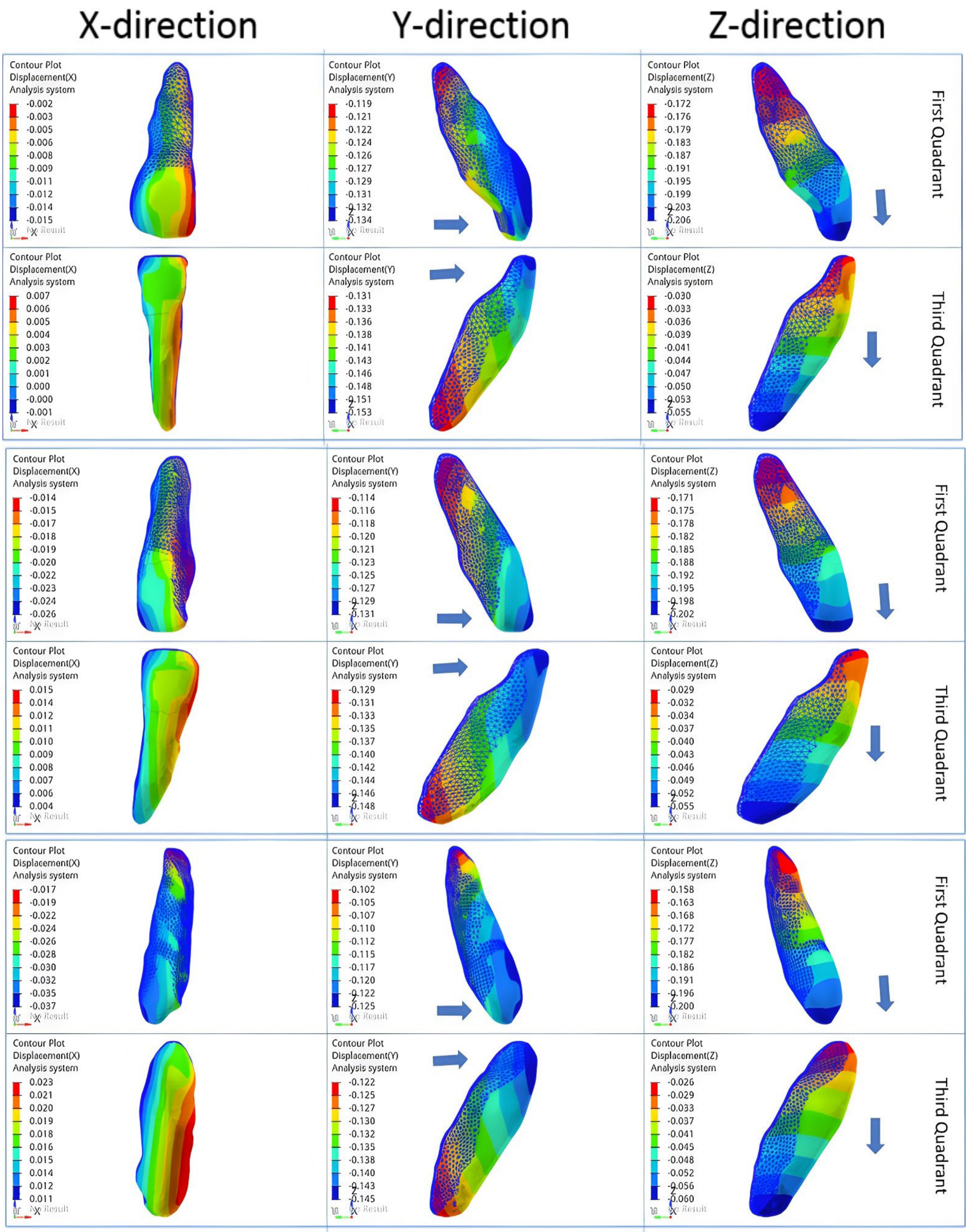

Figure 7: Movement of central, lateral and canine teeth with combined thermo-mechanical static structural analysis in first and third quadrant at 740 nm frequency and the arrow representing the direction of movement.

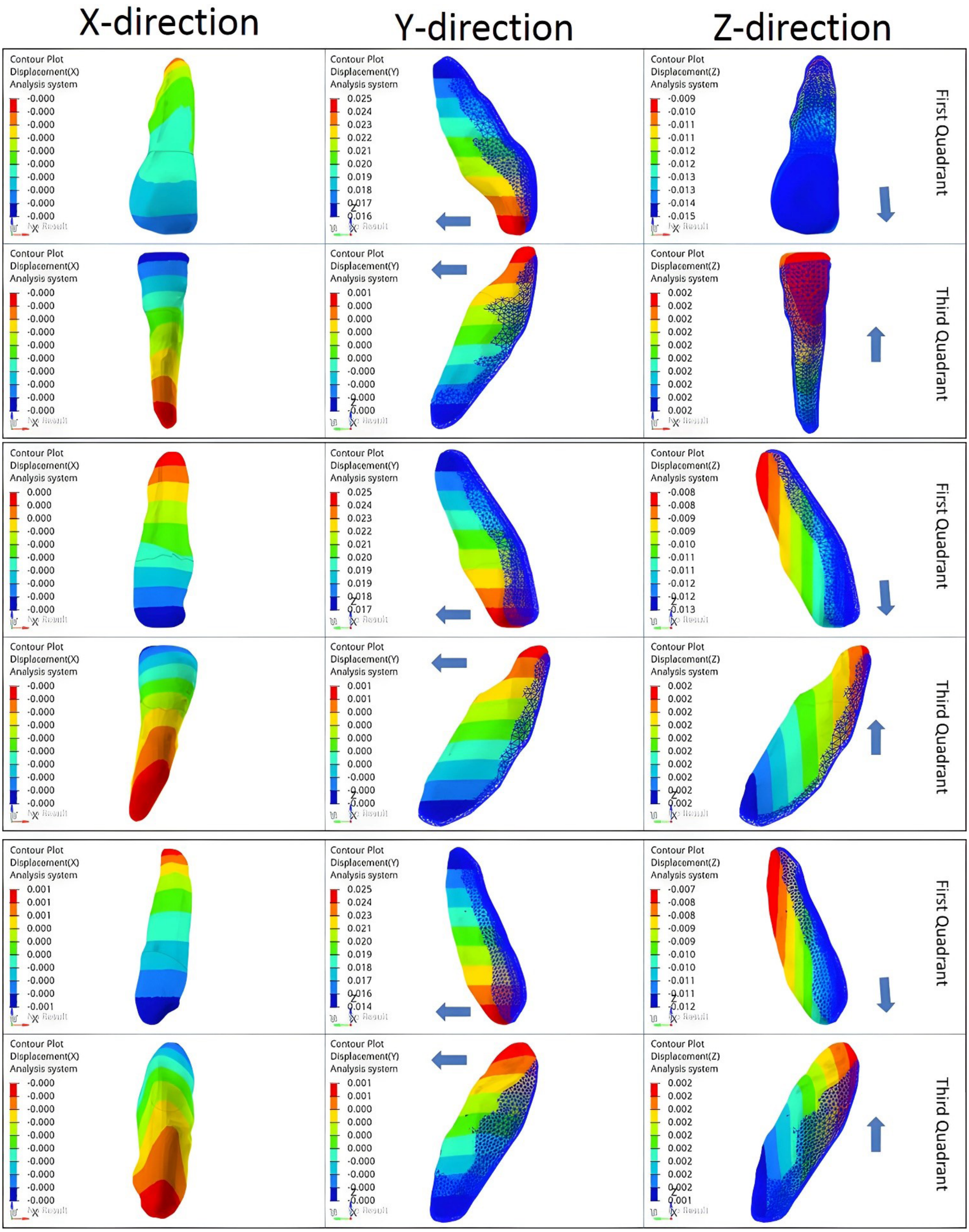

Figure 8: Movement of central, lateral and canine teeth with combined thermo-mechanical static structural analysis in first and third quadrant at 850 nm frequency and the arrow representing the direction of movement.

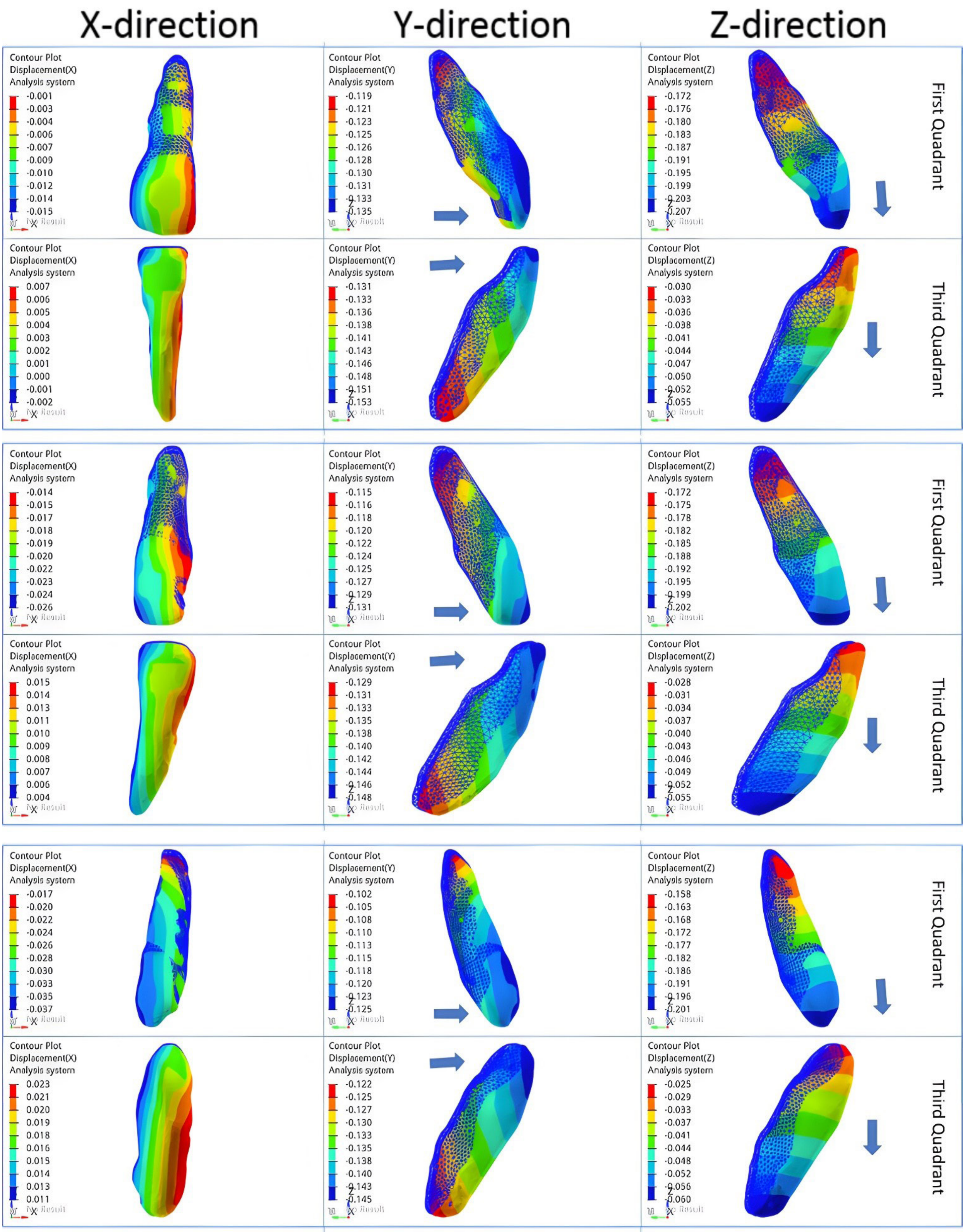

Figure 9: Movement of central, lateral and canine teeth with combined thermo-mechanical static structural analysis in first and third quadrant at 940 nm frequency and the arrow representing the direction of movement.

in the periodontium [15]. The Finite Element Analysis (FEA) approach is extensively employed for the determination of stress and deformations in intricate structures characterized by diverse geometries that are not amenable to analytical solutions. The complicated structures are partitioned into smaller pieces that are interconnected, and the forces exerted on the boundaries are specified to confine the structure [16].

Since its initial implementation in the field of orthodontics by Yettram in 1972 [17], this technique has undergone significant improvement and has demonstrated a high level of precision in achieving desired outcomes. The finite element analysis technique is employed to evaluate the stresses and deformations induced by various elements such as pressure, external forces, thermal fluctuations, and others in the model under consideration.

Middleton et al. [18] did a study in which they observed that the data obtained through the FEM analysis exhibited greater accuracy in comparison to alternative experimental techniques. The FEM can be utilized to illustrate the effects of heat energy application, thermal changes, and the resulting stress in accordance with engineering principles and equations.

Table 2: Parameters used for the study

Wavelength (nm)	Energy density (J/sq cm)	Power output (mw)
740	8	51
850	4	26
940	15	93

Freq	740 nm			First Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.025	-0.015	0	0.025	-0.013	0.001	0.025	-0.012
Combined	-0.015	-0.134	-0.207	-0.026	-0.131	-0.202	-0.037	-0.125	-0.2
Freq	740 nm			Third Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.001	0.002	0	0.001	0.002	0	0.001	0.002
Combined	0.007	-0.153	-0.055	0.015	-0.148	-0.055	0.023	-0.145	-0.06
Freq	850 nm			First Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.025	-0.015	0	0.025	-0.013	0.001	0.025	-0.012
Combined	-0.015	-0.134	-0.207	-0.026	-0.131	-0.202	-0.037	-0.125	-0.2
Freq	850 nm			Third Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.001	0.002	0	0.001	0.002	0	0.001	0.002
Combined	0.007	-0.153	-0.055	0.015	-0.148	-0.055	0.023	-0.145	-0.06
Freq	940 nm			First Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.025	-0.015	0	0.025	-0.013	0.001	0.025	-0.012
Combined	-0.015	-0.135	-0.207	-0.026	-0.131	-0.202	-0.037	-0.125	-0.201
Freq	940 nm			Third Quadrant					
Load Case	Central Incisor			Lateral Incisor			Canine		
	X	Y	Z	X	Y	Z	X	Y	Z
Structural	0	0.001	0.002	0	0.001	0.002	0	0.001	0.002
Combined	0.007	-0.153	-0.055	0.015	-0.148	-0.055	0.023	-0.145	-0.06

Figure 10: The results and inference with both structural and combined analysis with central, lateral and canine tooth in first and third quadrant with 740,850 & 940 nm of frequency.

Given the challenges associated with directly accessing the photo biomodulation (PBM) effects, our investigation aimed to determine the thermal output produced by LED lights emitting three distinct wavelengths, ranging from visible red to near-infrared frequencies of 740, 850, and 940 nm. Specifically, we examined the impact of this thermal output on soft tissues and its influence on expediting orthodontic tooth movement. To establish a comparative analysis, we contrasted these findings with the conventional approach of orthodontic fixed appliance treatment, utilizing a force of 70 gm, as simulated through FEM.

A force of 70 gm was selected for our investigation, as our research purpose was to address mild to moderate crowding, which typically requires a lower magnitude of the force in the anterior region. According to Proffit et al. [19], the ideal forces required for tipping, intrusion, extrusion, and rotation correction in orthodontics range from 35 to 60 gm, while body movement needs forces between 70 and 120 gm. A force magnitude of 70 gm was chosen primarily to minimize the potential for sporadic physiological adjustments in cases of mild to moderate crowding during the initial treatment of malocclusion.

Numerous investigations have been undertaken in previous research endeavors pertaining to the utilization of light on oral tissues and its consequential temperature impacts. In a study conducted by Amuk NG et al. [20], the objective was to investigate the thermal and cooling time associated with orthodontic bonding using LED lights. The findings of the study indicated that there was a noticeable rise in temperature and exposure duration, which might be related to the use of higher parameters. The existing body of literature has indicated that the effects of correction are influenced not only by the wavelength of the frequencies employed, but also by the energy density and power output [21].

The study conducted by Wilson TM et al. has provided scientific evidence supporting the efficacy of faster accelerated orthodontic tooth movement within the parameters of 4-8 J of energy density, 780-904 nm of wavelength, a power output of 10-120 mW, and an exposure time of 80-100 s in a randomized controlled trial (RCT) [22]. In this work, we conducted a comparative analysis of three distinct frequencies of wavelengths utilizing the FEM model. Various factors were employed to investigate the impact of heat generation on tissues and its potential for expediting orthodontic therapy through PBM.

In our study model built using the FEM, we employed a split-mouth technique. This choice was made due to the inherent advantages of the split-mouth design, which allows for intra-patient comparison while maintaining the patient's personal control. This design facilitates clinical correlation. Based on the simulation results and observations, our study found that tooth movement was more pronounced in the static structural analysis when subjected to applied loads and boundary conditions with frequencies of 740 nm, 850 nm, and 940 nm. This movement was observed in both the Z and Y directions across all four quadrants during mechanical loading, specifically with a force of 70 gr. In the context of combined thermal-mechanical static analysis, it was observed that there was an increased displacement of teeth in the -Y and -Z directions in both the 1st and 3rd quadrants across all three frequencies. This observation was made based on the study of displacement contours and heat generation.

Given that our study was conducted using three specific frequencies, it is advisable to do more research including a wider range of frequencies and characteristics in order to ascertain the impact of LED light frequencies on soft tissues.

Conclusion

Based on the simulation findings and empirical observations, the loads and boundary conditions were applied. The investigation yielded the following conclusions across various frequencies, as follows: higher tooth movement was seen when a combined loading case was applied across all frequencies (740 nm, 850 nm, and 940 nm); elevated displacements were detected in the buccolingual and vertical dimensions; through the utilization of static structural analysis, it was determined that tooth displacements occurred in both the Z and Y directions across all three frequencies inside each of the four quadrants; in the context of a combined mechanical static thermal study, it was observed that the 1st and 3rd quadrants exhibited greater tooth motions in the -Y and -Z directions across all three frequencies; the results of the transient thermal study indicated that the temperatures and heat generation were observed to be highest at a wavelength of 940 nm, followed by 740 nm and 850 nm. Clinical significance: The LED frequencies 740, 850, and 940 nm produced faster tooth movements, and 940 nm generated the most heat, followed by 740 nm and 850 nm.

Authors' Contribution

Kh. Riyaz Conceived the idea. The introduction was written. Gathered the literature, images, and writing-related works. The methodology implementation and results were analyzed and carried out. PG. Shivamurthy Contributed to the introduction part, gathered related literature work & images. Contributed to methodology implementation and results. Finally, both authors read, modified, and approved the final version of the manuscript.

Ethical Approval

No ethical clearance is needed in this study as it is FEM simulation-based.

Conflict of Interest

None

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