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Biomechanical and Vibrational Investigation of Human Femur Bones: Finite Element Insights into Osteoporotic and Healthy Conditions

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Abstract

Osteoporosis is a bone disease that makes bones weaker over time and considerably increases the risk of femoral fractures. The biomechanical and vibrational properties of the human femur in both healthy and osteoporotic situations are examined in this investigation through the use of finite element analysis (FEA). 3D models created from CT were simulated through modal and static structural analyses under physiologically appropriate loading conditions, including stair climbing, walking, sitting, and standing. The osteoporotic femur exhibited a loss of stiffness and dynamic stability, accompanied by a 20–36% reduction in natural frequencies under boundary conditions. Structural analysis further revealed that the osteoporotic model exhibited up to four times greater deformation and von Mises stress compared to the healthy femur, with peak stresses reaching 146.51 MPa when climbing stairs. These findings provide insights into the mechanical changes associated with osteoporosis, aiding early detection, fracture risk assessment, and targeted rehabilitation. Integrating artificial intelligence and machine learning is proposed to enhance predictive modeling and personalized orthopedic care. This analysis contributes to understanding femoral mechanics and advancing precision orthopedics for managing osteoporosis and related skeletal conditions.

Keywords: Finite Element Analysis (FEA), Biomechanical Analysis, Fracture Risk Assessment, Natural Frequencies, Bone Density

1. Introduction

The human femur is the longest and strongest bone in the body, plays a crucial role in supporting weight and enabling movement. As the longest and strongest bone in the human body, the femur is subjected to various mechanical stresses and loads throughout a person's lifetime, making it susceptible to fractures and other bone-related disorders. However, Osteoporosis in the femur refers to a condition where the bone becomes weakened due to a decrease in bone mineral density (BMD) (Figure 1.1), making it more susceptible to fractures [1]. This condition mostly affects elderly people and postmenopausal women, making them more susceptible to fractures and more vulnerable, which significantly lowers their quality of life and raises the cost of healthcare. Understanding the mechanical and vibrational behavior of osteoporotic femur bones compared to healthy ones is essential for improving early diagnosis, fracture prevention, and treatment strategies. Finite Element Analysis (FEA) is widely used in biomedical engineering to simulate and evaluate the biomechanical performance of bones under different loading and boundary conditions [2]. It provides detailed insights into stress distribution, deformation, and failure zones within bone structures. In this analysis, FEA was used to analyze patient-specific femur models,

one representing a healthy 45-year-old male and the other an osteoporotic 69-year-old female, generated from computed tomography (CT) data. The models were analyzed using modal (vibrational) and static structural analyses in physiologically relevant scenarios, such as standing, sitting, walking, and climbing stairs.

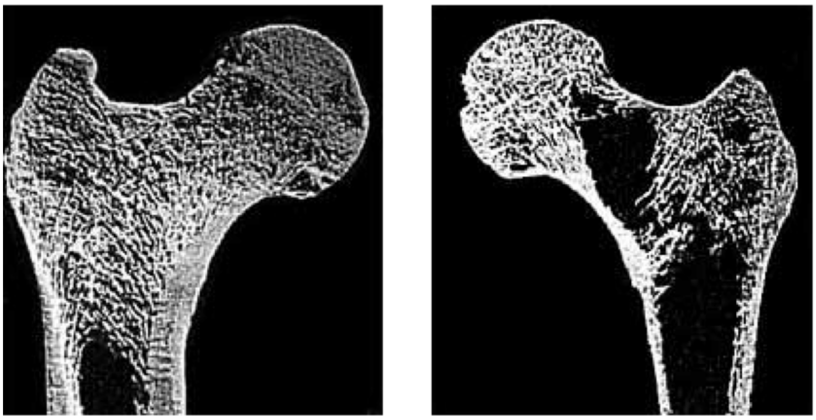

Figure 1.1: Healthy femur (left) vs. osteoporotic femur (right), illustrating significant bone density loss in osteoporosis [3].

For modal analysis, three different types of boundary conditions were taken into consideration to recreate various clinical and anatomical limitations: free-free, fixed-fixed, and fixed-frictionless. Structural simulations evaluated stress, strain, and deformation responses under scaled body weight loads for daily activities. The effects of disease progression on dynamic stability were examined by comparing the vibrational characteristics, especially natural frequencies, of osteoporotic and healthy bones. Unusual changes in vibrational characteristics might be an indicator of osteoporotic changes and a symptom of additional problems with bone health [4]. This study addresses a critical gap by performing an integrated vibrational and biomechanical analysis on both healthy and osteoporotic femurs under identical, patient-specific conditions. The principal novelty of our work lies in this concurrent dual methodology approach, which provides an integrated framework to quantitatively assess how osteoporosis simultaneously degrades the bone's dynamic stability (through modal analysis) and its static load-bearing capacity (through structural analysis). These studies not only align with current clinical observations but also support the future application of artificial intelligence (AI) and machine learning (ML) to build predictive tools for fracture risk and patient-specific treatment planning. This research thereby contributes to the development of more personalized and preventive orthopedic care systems.

2. Background

Bhandari et al. utilized Finite Element Analysis on a CAD model of the human femur, developed from 3D scans, to evaluate stress sensitivity under various loads, identifying maximum stress and potential failure areas [5]. Taylor et al. employed active shape models and Finite Element Analysis to predict fracture risk in postmenopausal women, with a focus on cortical thickness and bone density distribution. Their study highlighted how important it is to combine FEA and active models to evaluate fracture risk and guide focused therapies [6]. Miura et al. used several mesh sizes to create a CT-based FEA model that predicts fracture stress and stiffness in the proximal femur. With significant correlation between expected and actual fracture loads, this work improves the validity of bone strength evaluations, especially for elderly osteoporosis patients [7]. Bessho et al. used a CT-based finite element analysis to estimate strength and strain in the proximal femur, aiming to improve fracture risk assessment in older patients with osteoporosis. Their work validated the accuracy of FEA through simulation and cadaver testing, contributing to the understanding of bone mechanics and fracture prediction [8]. Molino et al. explored osteoporosis-related variations in bone properties, revealing significant differences in microstructure, mineral composition, and mechanical behavior between healthy and osteoporotic femurs. Their findings provide essential insights for understanding bone health and osteoporosis-related disorders [9].

Kumar and Parhi investigated the human femur's vibrational characteristics and stress analysis to comprehend how it reacts to different loading scenarios during both static and dynamic activity. They evaluated natural frequencies, mode shapes, and stress distributions using finite element modeling to find out possible damage zones and safe operating ranges [10]. Kumar et al. utilized finite element analysis to investigate the free vibration modes of the femur under various boundary conditions, aiming to identify natural frequencies, vibration modes, and potential fracture sites. Their research seeks to forecast fracture locations and enhance injury prevention by avoiding resonance with external frequencies, thereby improving femoral bone mechanics and fracture prevention strategies [11]. Gautam and Rao presented a multiscale modeling technique for analyzing the mechanical properties of the human femur using ANSYS's Computational Multiscale Analysis System (CMAS). Their approach involves homogenizing microscale material properties into macroscale models, including the development of a microscale model, numerical material testing, and finite element analysis [12]. Vijayakumar and Madheswaran analyzed the mechanical characteristics and stress responses of the femur using finite element techniques, identifying that horizontal fracture position 2 had the highest Von Mises stress. They emphasized avoiding resonance with the femur's natural frequency to reduce fracture risk, particularly in the neck and shaft, to guide biomechanical tool and sports equipment design [13]. Reddy et al. focused on the use of finite element analysis (FEA) and sophisticated imaging techniques to evaluate bone density and fracture risk, notably in the femur. Researchers discovered that younger people have normal bone density, but older people have osteopenia or osteoporosis, which increases their risk of fractures [14]. Minuye and Gizaw investigated the modal and vibration properties of femur bones using Finite Element Method (FEM) simulations, identifying natural frequencies and mode shapes under free-free and fixed-fixed boundary conditions. Their findings indicated that fractures are most likely to occur in the neck or shaft of the femur, particularly when external vibrations align with the bone's natural frequencies [4].

3. Methodology

3.1 Model Creation

With the desire to study the biomechanical behavior of the femur bone, 3D models were developed from the MRI scanning technique. The healthy femur model was generated from a 45-year-old male (85 kg) **(Figure 3.1.1)**, while the osteoporotic femur was reconstructed from a 69-year-old female (79 kg) **(Figure 3.1.2)**. This pairing was intentionally chosen to reflect a clinically representative scenario because postmenopausal women are considered the highest risk population for osteoporosis. While anatomical variations exist between genders, this comparison provides a functionally relevant assessment of the disease's impact by contrasting a typical at-risk patient cohort against a standard healthy baseline for a common and valid approach in comparative biomechanical studies. The reconstructed models were then converted into IGES format and imported into ANSYS for finite element analysis, where the geometry was discretized into finite elements for computational simulations.

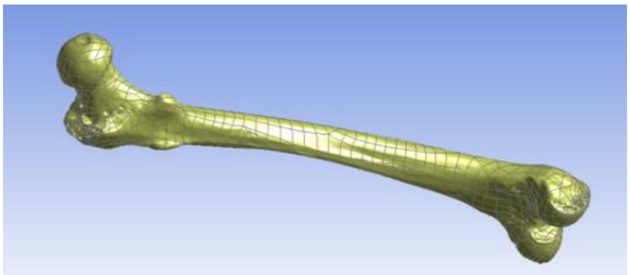

Figure 3.1.1: Femur Bone of the healthy person exported into IGES format.

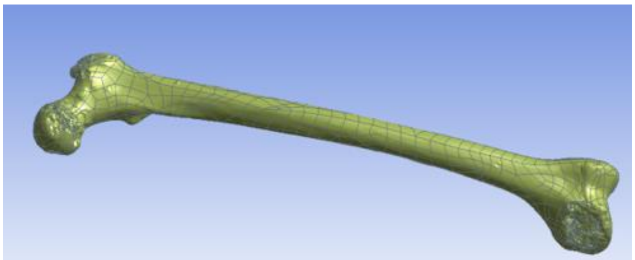

Figure 3.1.2: Femur Bone of the osteoporosis person exported into IGES format.

3.2 Mesh generation

For accurate finite element analysis, both the healthy (45-year-old male) shown in **(Figure 3.1.1)** and the osteoporotic (69-year-old female) shown in **(Figure 3.1.2)** femur geometries were meshed using Solid187 quadratic tetrahedral (Tet10) elements in ANSYS. Given the anatomical complexity of the femur—especially around the femoral neck, greater trochanter, and distal condyles—a patch-conforming method was used to ensure high mesh fidelity and smooth element transitions. To balance precision and computational efficiency, an element and body sizing strategy was applied; the meshing consists of the following values, as shown in **(Figure 3.2.1 & Figure 3.2.2).**

For the healthy bone,
Number of nodes = 205173
Number of elements = 142091
For the osteoporotic bone,
Number of nodes = 522926
Number of elements = 357372

Later boundary conditions were applied to carry out further analysis on the finite element model.

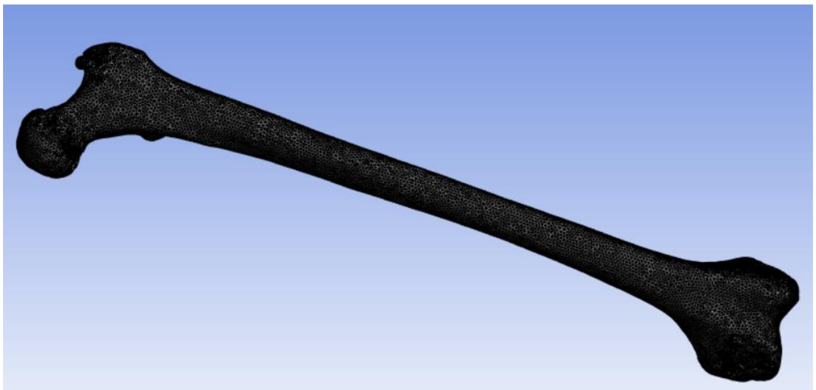

Figure 3.2.1: Meshing of osteoporosis bone.

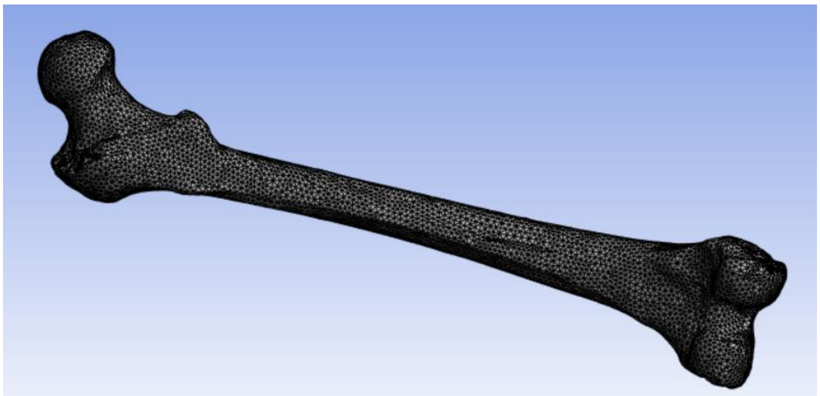

Figure 3.2.2: Meshing of healthy bone.

3.3. Bone Material Selection for Healthy and Osteoporotic Conditions

The femur is a long bone with two different bone types: cortex (compact) and cancellous (trabecular). Cortical bone is the thick outer layer that accounts for around 80% of the bone's overall mass, whereas cancellous bone is the interior, porous portion. To maximize computational efficiency, the femur model was simplified to focus on the cortical bone for this investigation. For finite element analysis, the key biomechanical features of the femur are retained by representing it as a solid cylindrical structure with a central marrow hollow. This should highlight the mechanical behavior of bone. Although bone is usually thought of as a perfectly rigid material, it is actually a composite biological tissue that displays linear elastic behavior under normal physiological loading conditions. Under physiological loads induced during walking or climbing stairs, for example, bone undergoes small, recoverable deformations, strains, and internal stresses, predictable by Hooke's Law. The observed deformations and mode shapes from this study represent this inherent elasticity. Once the load on the bone is removed, it is assumed to return to its original shape, a basic assumption of our linear static and modal analyses. Young's Modulus values (E), as defined in this section, quantify this stiffness and directly control the magnitude of deformation and vibrational response in our model. Since bone material properties are not available in the ANSYS engineering data library, a specific material dataset was created. This dataset includes mechanical parameters from peer-reviewed literature that indicate the different features of both healthy and osteoporosis bone states. These properties (Table 3.3.1) include density, Young's modulus, and Poisson's ratio.

Property	Healthy Bone	Osteoporosis Bone	Reference
Density (ρ)	1.95 g/cm^3	1..45 g/cm^3	[15]
Young's Modulus (E)	18.5 GPa	12 GPa	[15]
Poisson's Ratio (ν)	0.3	0.23	[15]
Ultimate Compressive Strength	195 MPa	115 MPa	[15]
Ultimate Strength Tensile	105 MPa	65 MPa	[15]

Table 3.3.1: Comparison of Mechanical Properties Between Healthy and Osteoporotic Cortical Bone

3.4 Boundary Loading Conditions

Boundary and loading conditions are essential for simulating realistic mechanical and vibrational scenarios in femur analysis. The following conditions were explored:

3.4.1. Vibration Analysis:

The identification of natural frequencies and mode shapes under three boundary conditions provides insights into the vulnerability of specific femoral regions to fractures, especially when external vibrations resonate with the bone's natural frequencies.

Free-Free Boundary Condition: In this configuration, the femur model is unconstrained at both ends, allowing for unrestricted movement and rotation in all directions. This setup is typically used in modal analysis to identify natural frequencies and mode shapes without the influence of supports.

Fixed-Fixed Boundary Condition: Both the femoral head (proximal) and distal condyles are fully constrained (Figure 3.4.1). This boundary condition simulates a rigid experimental setup and is primarily utilized in modal analysis to eliminate rigid body modes, ensuring meaningful vibration modes.

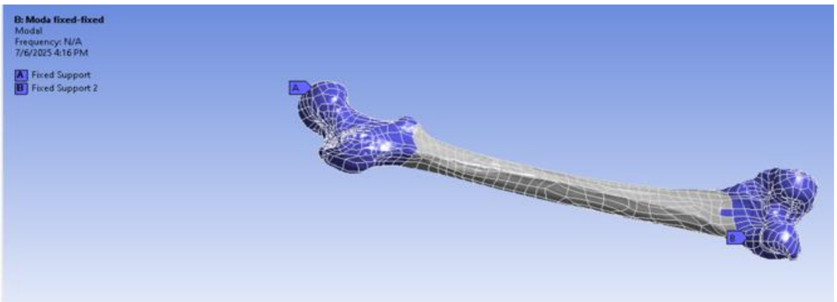

Figure 3.4.1: Fixed-Fixed support of bone.

Fixed-Frictionless Boundary Condition: In this configuration, the distal end is fixed while the femoral head is assigned a frictionless support **(Figure 3.4.2).** This allows for vertical translation but no lateral resistance, simulating hip joint behavior more closely than the fully free condition, particularly during walking and standing

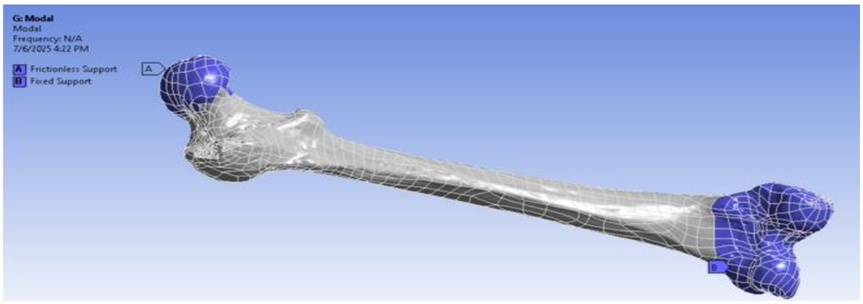

Figure 3.4.2: Fixed–Frictionless support of bone

3.4.2 Biomechanical Analysis

All biomechanical simulations were conducted using the Remote Force application in ANSYS to replicate physiological loading conditions on the human femur (see Table 3.4.2). This method enables the application of forces at specific anatomical points, such as the femoral head, while accurately transmitting force components in the X (Medial-Lateral), Y (Posterior-Anterior), and Z (Inferior-Superior) directions.

Activity	Approx. Load (× Body Weight)	Description
Standing (2-leg)	0.5×Body weight	Simulates bipedal load support.
Sitting	0.3×Body weight	Femur under flexion, low axial stress.
Walking	1.2×Body weight	Dynamic ground reaction forces.
Stair Climbing	2.5×Body weight	Inclined loading across the femoral shaft.

Table 3.4.2: Activity-Based Femoral Loading [16].

The force magnitude was customized for each model based on body weight (e.g., (85×9.81=834N) for healthy individuals and (79×9.81=775N) for osteoporosis bone. This approach ensures that force transmission and moment behavior closely replicate real-world loading conditions while maintaining a computationally efficient and anatomically accurate setup.

4. Result

4.1 Vibrational Analysis Result:

The vibrational analysis of both femurs was conducted using finite element modeling to evaluate their dynamic response under various boundary conditions: free-free, fixed-fixed, and fixed-frictionless. The primary objective was to identify natural frequencies and mode shapes, which are critical for understanding the bone's mechanical behavior and potential fracture risks. Also, the analysis was performed on an osteoporotic femur model to investigate the effects of reduced bone density and structural degradation on its dynamic response. The model, derived from a 69-year-old female subject, reflects typical characteristics of osteoporotic bone such as decreased elastic modulus and reduced mass, leading to notable changes in vibrational behavior.

Free-Free Mode:

Mode	Frequency (Hz) Healthy Bone	Frequency (Hz) Osteoporosis Bone
1–3	0	0
4–5	5.56×10-4 – 8.58×10-4	4.7904×〖10〗^(-4)-6.6726×〖10〗^(-4)
6	302.63	1.0846×〖10〗^(-3)
7	339.00	216.24
8-11	690.23 – 1055.6	221.12-670.99

Table 4.1.1: Simulated Results for free-free condition in both bones.

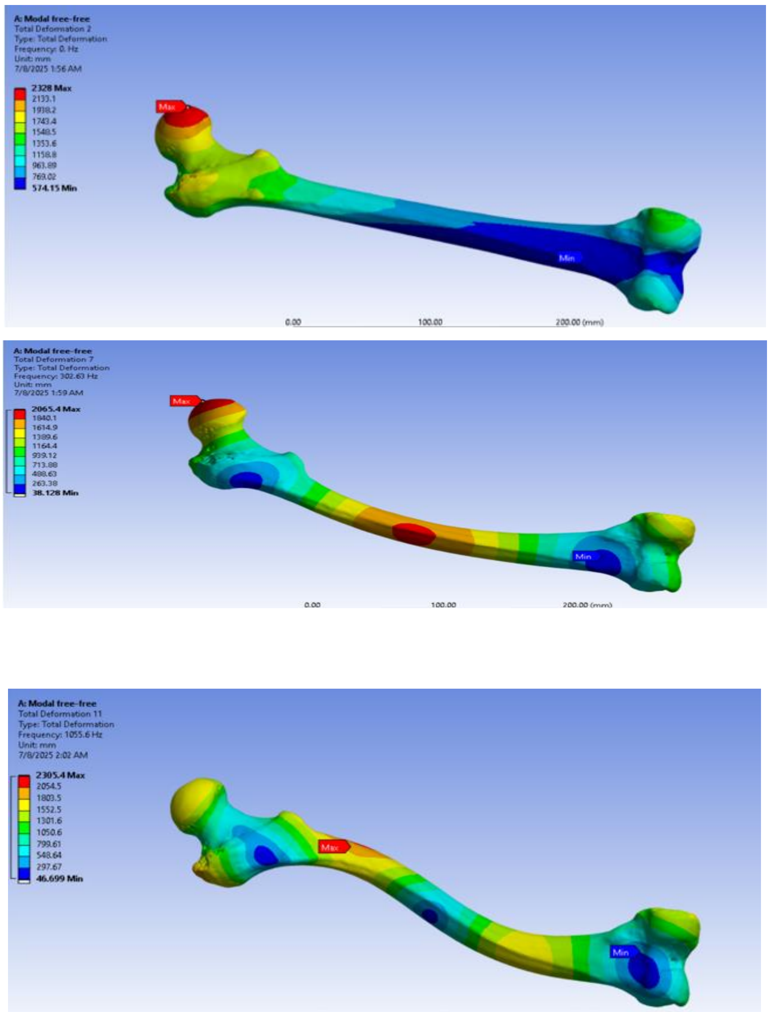

Figure 4.1.1: (a) Second mode shape (Free-Free, Healthy), (b) Seventh mode shape (Free-Free, Healthy), (c) Tenth mode shape (Free-Free, Healthy).

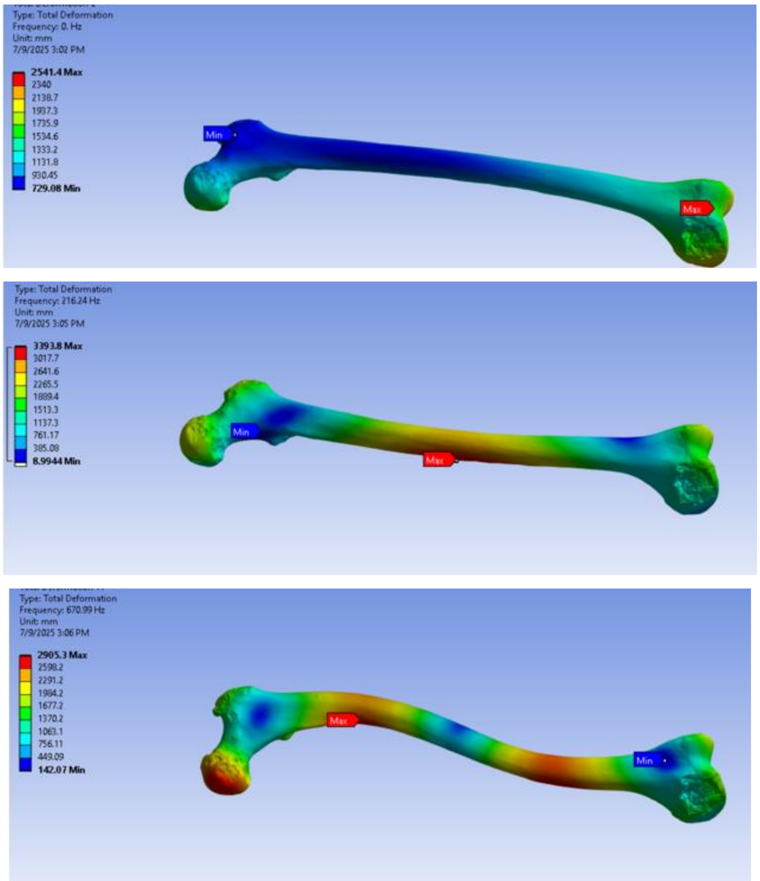

Figure 4.1.2: (a) Second mode shape (Free-Free, Osteoporotic), (b) Seventh mode shape (Free-Free, Osteoporotic), (c) Tenth mode shape (Free-Free, Osteoporotic).

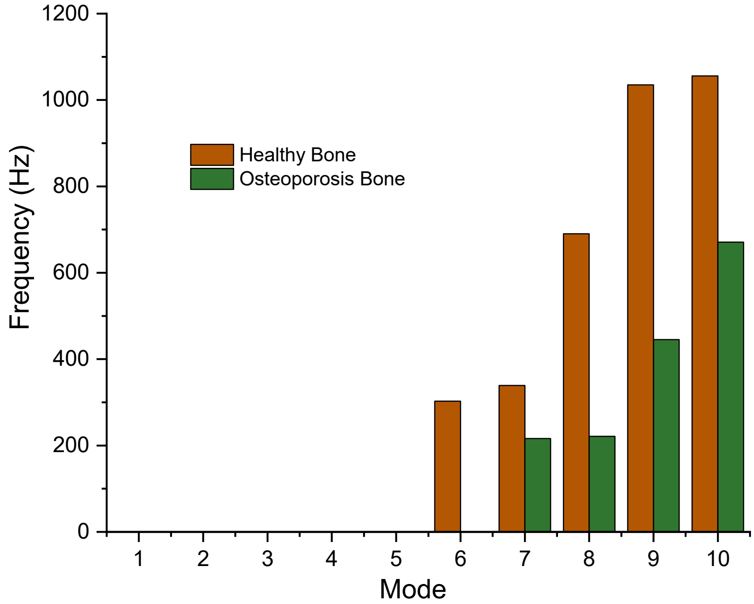

Figure 4.1.3 Comparison of modal frequencies between healthy and osteoporotic femur bones under free-free boundary conditions

Modal analysis under free-free boundary conditions showed that osteoporotic and healthy femurs had separate natural frequencies **(Figure 4.1.1 & Figure 4.1.2)**. All modes showed higher modal frequencies **(Table 4.1.1)** in the healthy femur, with values ranging from roughly 0 Hz to 1055.6 Hz. The osteoporotic femur, on the other hand, displayed much lower frequencies **(Table 4.1.1)**, ranging from 0 Hz to approximately 670 Hz for the 10th mode. A significant loss in structural stiffness and bone mineral density was indicated by the bar chart **(Figure 4.1.3)**, which shows that the reduction in frequency for osteoporotic bone varied from 20% to over 36%, depending on the mode. These results are consistent with published research that indicates osteoporotic bones usually exhibit 20–30% lower natural frequencies as a result of reduced bone elasticity and density [4].

- **Fixed–Fixed Mode**

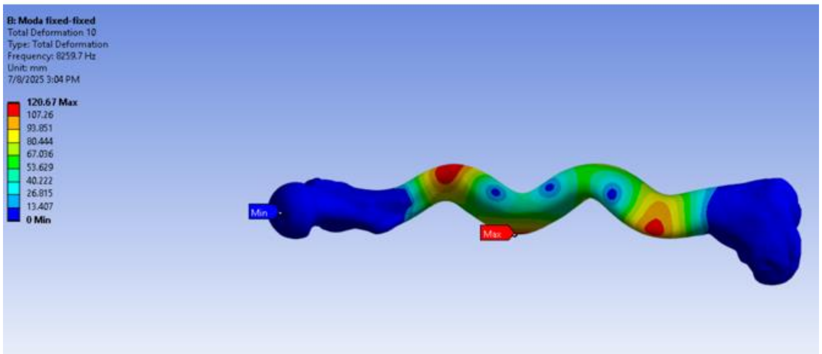

Figure 4.1.4: Tenth mode shape (Fixed-Fixed, Healthy)

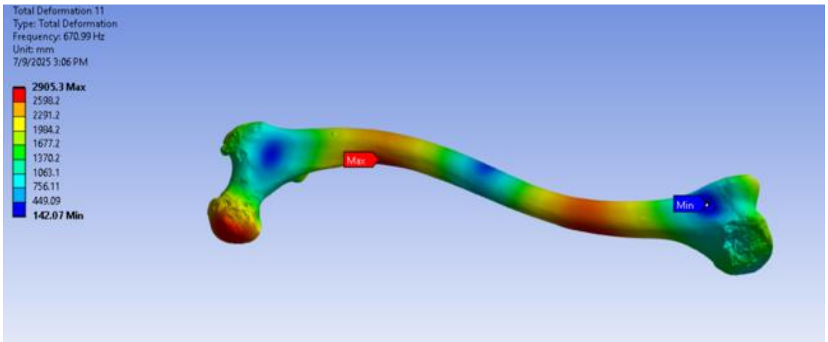

Figure 4.1.5: Tenth mode shape (Fixed–Fixed, Osteoporosis)

Mode	Frequency (Hz) of Healthy Bone	Frequency (Hz) of Osteoporosis Bone
1	1298.9	836.2
2	1375.2	929.03
3	3018	2058.7
4	3229.4	2279.6
5	4343.2	3207.9
6	5397.3	3766.7
7	5735.3	4091.7
8	6352.7	4870.7
9	7711.6	5707.3
10	8259.7	6112.5

Table 4.1.2: Simulated Results for Fixed-Fixed Condition in Both Bones

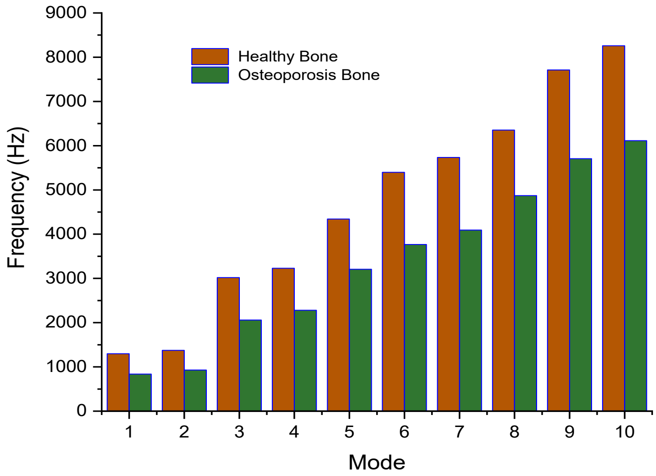

Figure 4.1.6 Comparison of modal frequencies between healthy and osteoporotic femur bones under fixed-fixed boundary conditions.

The vibrational responses of both osteoporotic and healthy femur bones displayed different modal frequency patterns under a fixed–fixed boundary condition. Across all vibration modes (Mode 1 to Mode 10), the healthy femur continuously displayed higher natural frequencies (Figure 4.1.4), with the maximum frequency reaching 8259.7 Hz, as shown in the bar chart (Figure 4.1.6). On the other hand, the osteoporotic femur displayed lower modal frequencies (Figure 4.1.5), peaking at about 6,112.5 Hz. A reduction in bone mineral density and stiffness, which significantly impacts the bone's dynamic stability, is the cause of this decline in the frequency of osteoporotic fractures. The altered vibrational behavior of osteoporotic bones is confirmed by the frequency difference between corresponding modes, which varies from 20% to more than 30%.

- **Fixed–Frictionless:**

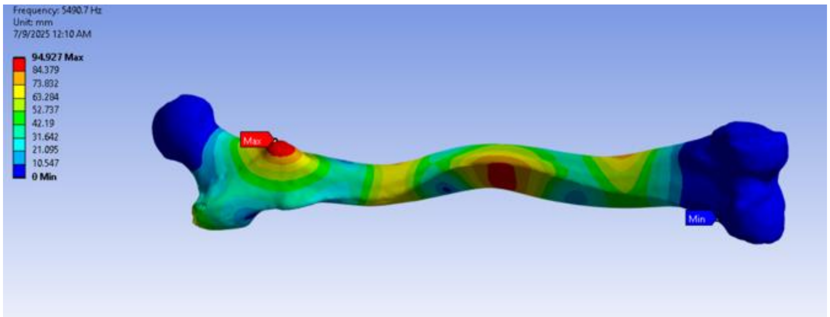

Figure 4.1.7: Tenth Mode Shape (Fixed-Frictionless, Healthy)

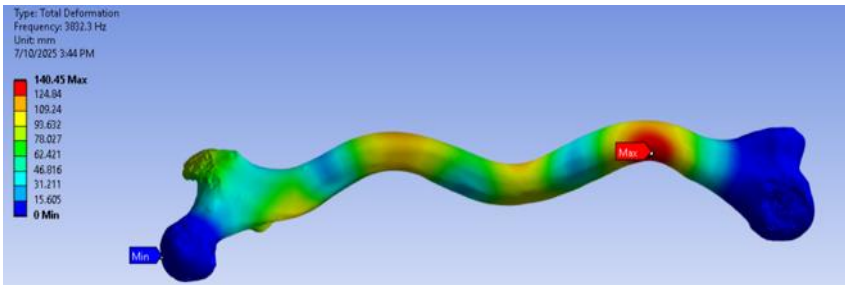

Figure 4.1.8: Tenth Model Shape (Fixed–Frictionless, Osteoporosis)

Citation: Shahariar., Md. T, Mesbah., M. M. T. I, ASM., S, Islam, R. (2026). Biomechanical and Vibrational Investigation of Human Femur Bones: Finite Element Insights into Osteoporotic and Healthy Conditions. *J Biomed Eng Res, 4*(4), 1-17.

Mode	Frequency (Hz) of Healthy Bone	Frequency (Hz) of Osteoporosis Bone
1	768.76	522.18
2	882.16	690.54
3	1763.8	1208.8
4	1983.3	1410
5	2604.1	1885.5
6	3159.7	2258.7
7	3643.3	2640.4
8	4114.0	3040
9	4561.1	3409.8
10	5490.7	3832.3

Table 4.2.3: Simulated Results for Fixed-Frictionless Condition In Both Bones

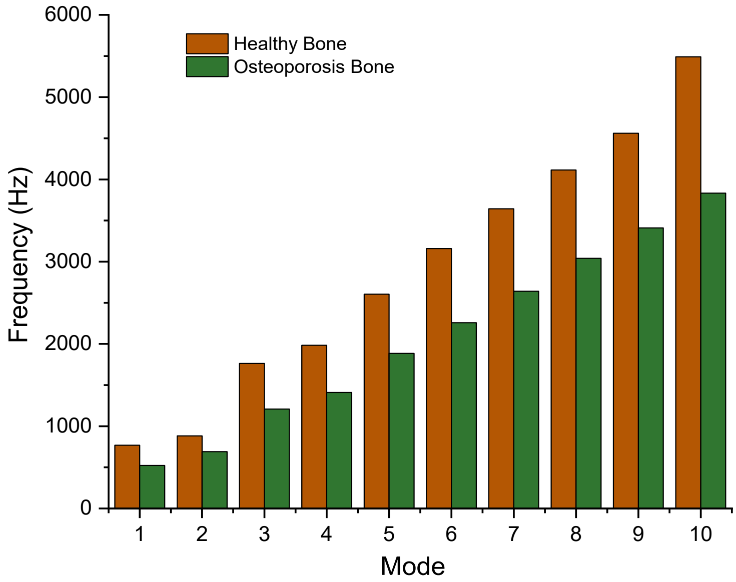

Figure 4.1.9: Comparison of Modal Frequencies Between Healthy and Osteoporotic Femur Bones Under Fixed-Frictionless Boundary Conditions

The vibration analysis of osteoporotic and healthy femur bones identified significant differences in their dynamic behavior under fixed-frictionless conditions. According to frequency response curves, the natural frequencies of the healthy femur in the bar chart (Figure 4.1.9) were consistently higher than those of the osteoporotic femur, with the former reaching a maximum of 5490.7 Hz across all modes under investigation. The healthy femur showed greater stiffness and structural integrity (Figure 4.1.7), as evidenced by a quantitatively significant increase in amplitude, especially in the higher frequency range. However, the osteoporotic femur exhibited less amplitude and lower natural frequencies (Figure 4.1.8), highlighting its weaker mechanical properties. These results highlight how osteoporosis affects the femur bones' vibrational properties, indicating a higher risk of fractures under dynamic loading scenarios.

4.2 Biomechanical Analysis Result:

The results of biomechanical simulations using finite element analysis (FEA) on models of healthy and osteoporotic bones are shown in this section (Table 4.2.1). Sitting, standing, walking, and stair climbing were among the daily activity-based loading conditions that were used. The outcomes are compared using the total deformation (Figure 4.2.1 & Figure 4.2.2) and the equivalent (von Mises) stress (Figure 4.2.3 & Figure 4.2.4)

Activity	Max Deformation (mm) of Healthy Bone	Von-Mises Stress (MPa) of Healthy Bone	Max Deformation (mm) of Osteoporosis Bone	Von-Mises Stress (MPa) of Osteoporosis Bone
Sitting	0.56367	4.3242	5.2498	18.126
Standing (0.5×BW)	0.92828	7.2549	7.9391	27.567
Walking (1.2×BW)	2.2456	17.318	17.476	75.269
Stair Climbing (2.5×BW)	4.2174	32.573	42.707	146.51

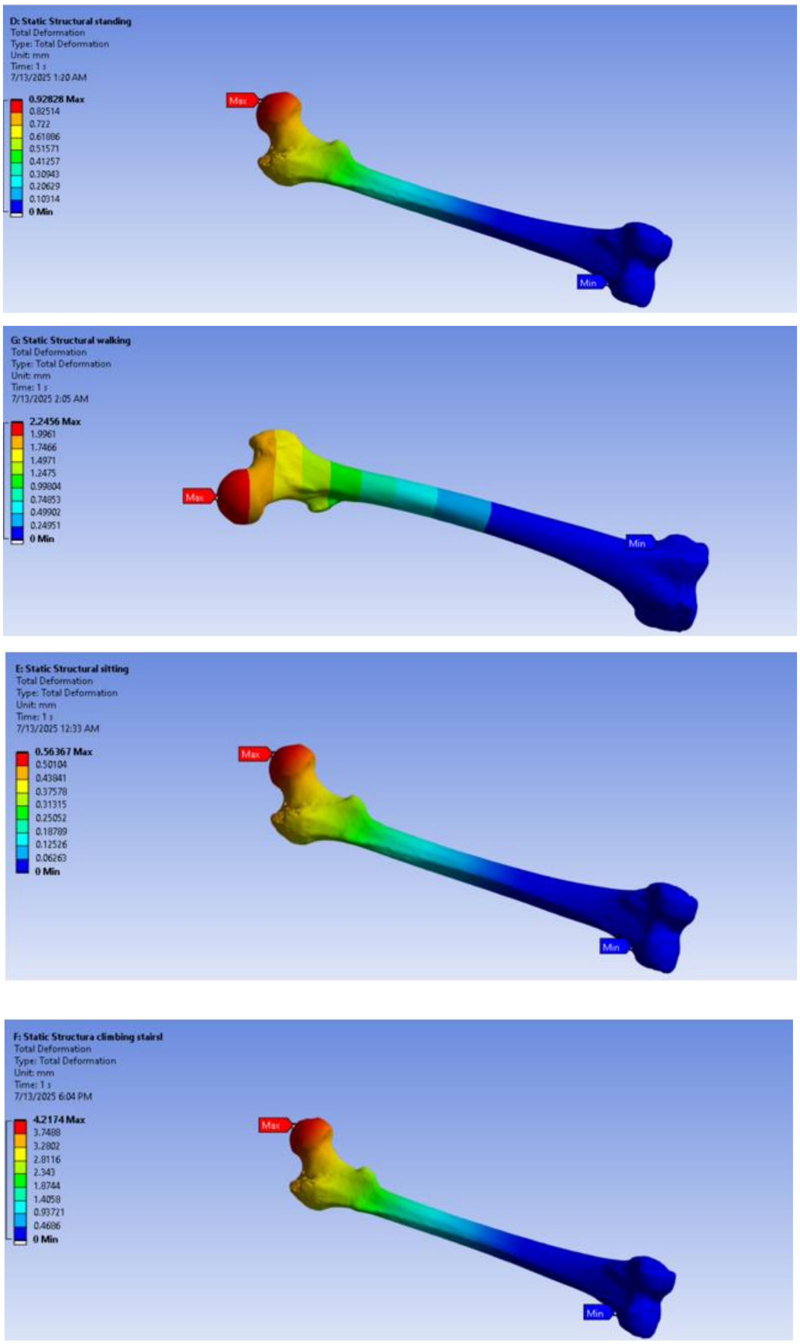

Figure 4.2.1: Total Deformation under (a) Sitting, (b) Standing, (c) Walking, and (d) Stair Climbing Loading Conditions of Healthy Bone.

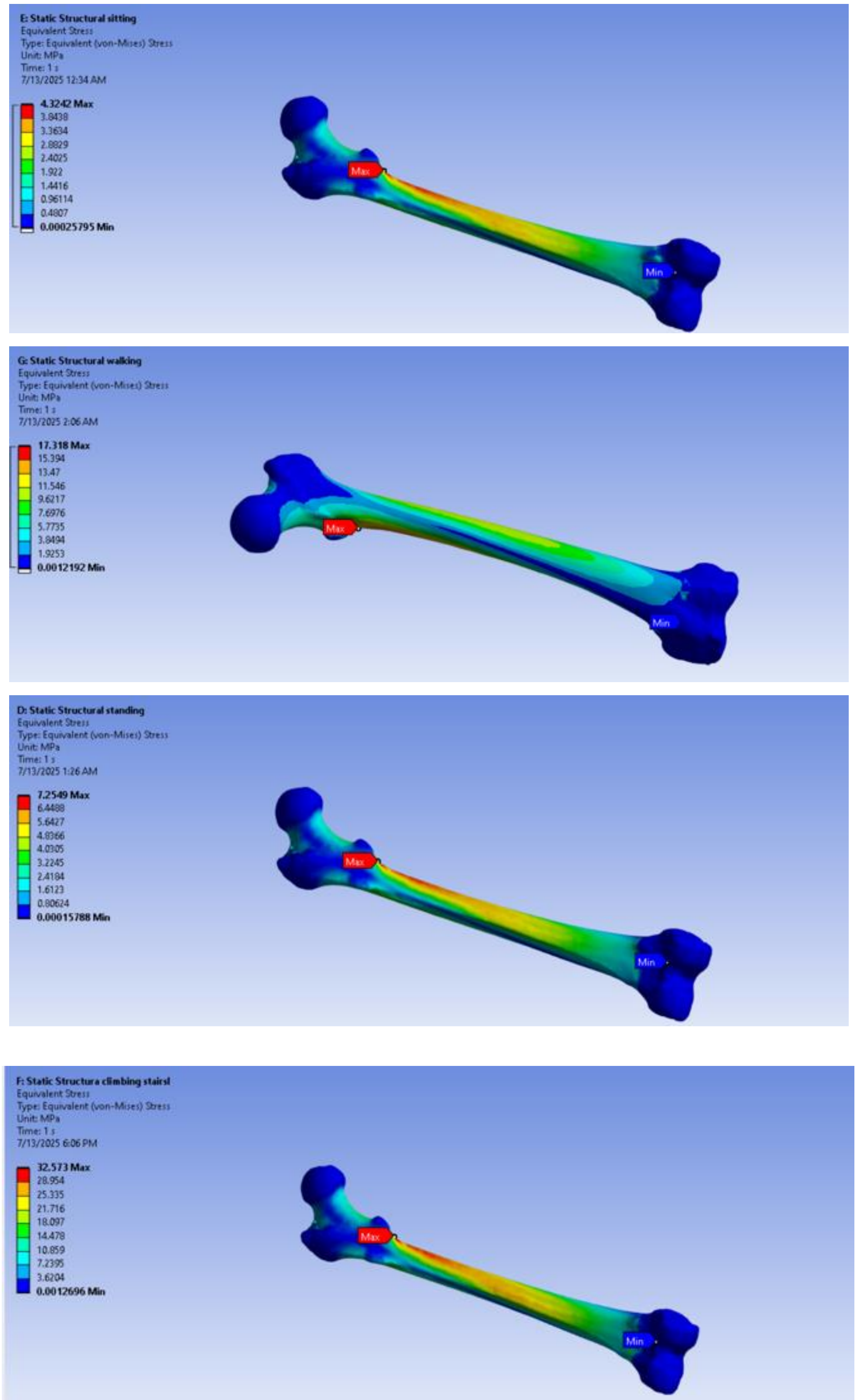

Figure 4.2.2: Equivalent Stress under (a) Sitting, (b) Standing, (c) Walking, and (d) Stair Climbing Loading Conditions of Healthy Bone

Citation: Shahariar., Md. T, Mesbah., M. M. T. I, ASM., S, Islam, R. (2026). Biomechanical and Vibrational Investigation of Human Femur Bones: Finite Element Insights into Osteoporotic and Healthy Conditions. *J Biomed Eng Res, 4*(4), 1-17.

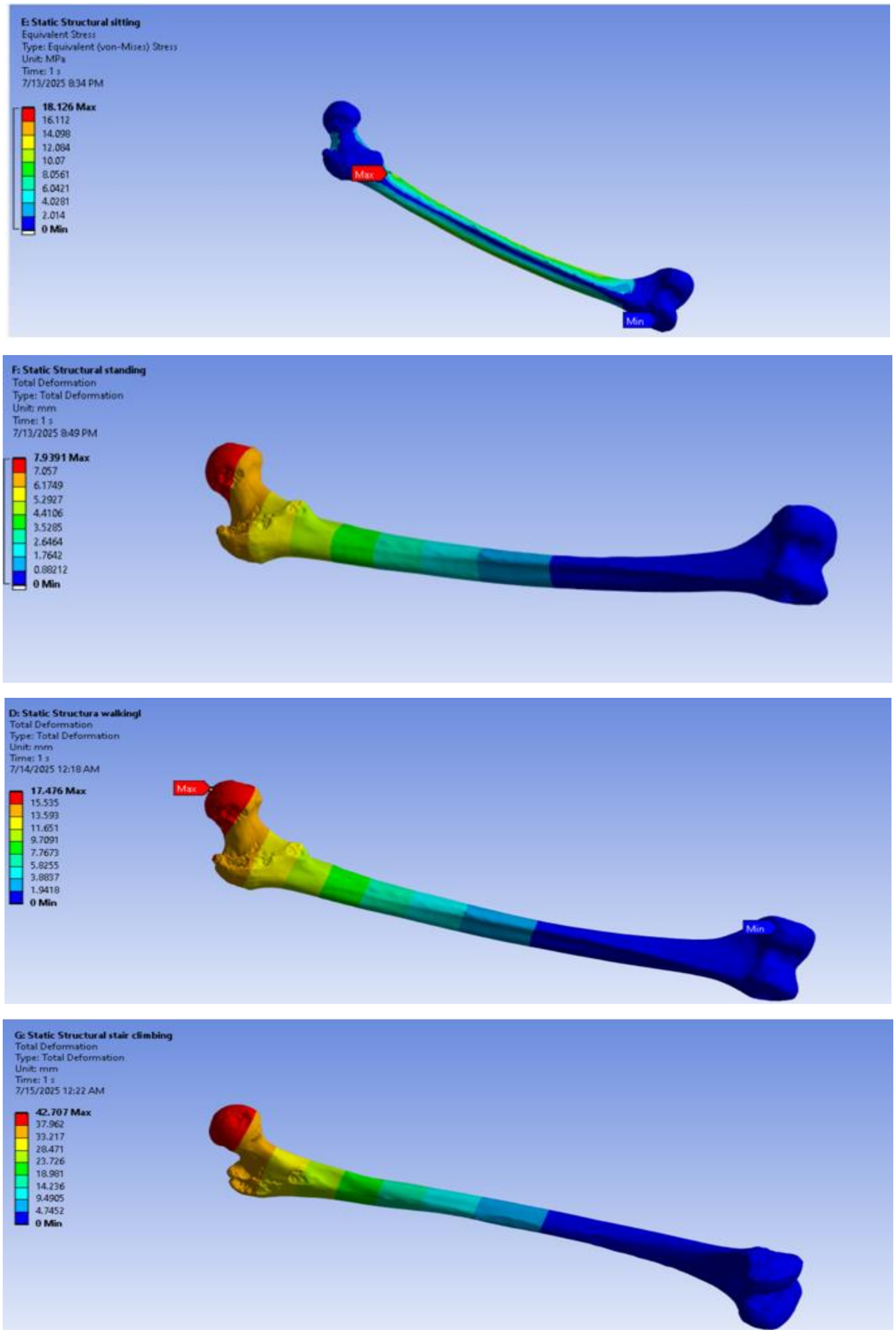

Figure 4.2.3: Total Deformation under (a) Sitting, (b) Standing, (c) Walking, and (d) Stair Climbing Loading Conditions of Osteoporosis Bone

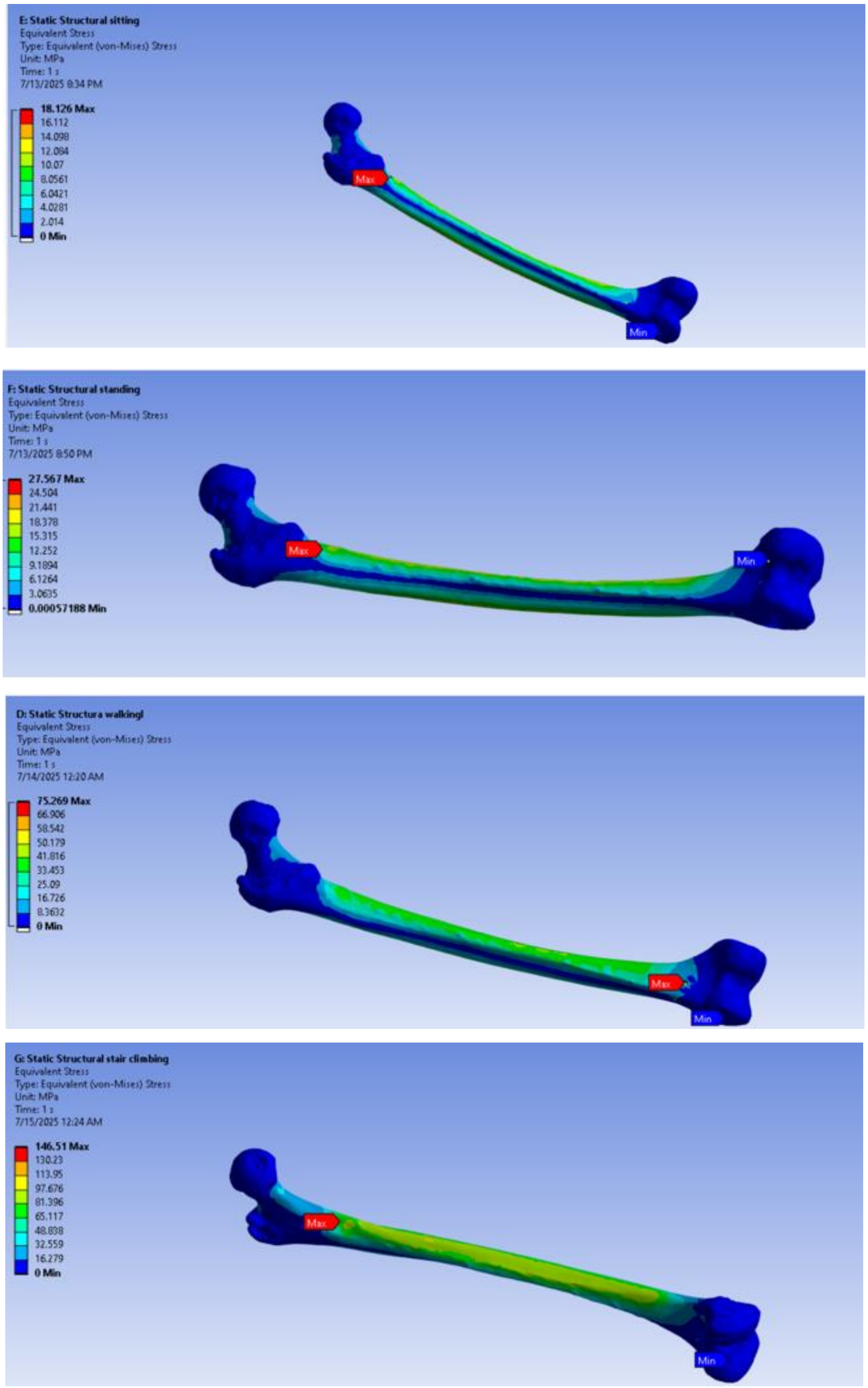

Figure 4.2.4: Equivalent Stress under (a) Sitting, (b) Standing, (c) Walking, and (d) Stair Climbing Loading Conditions of Osteoporosis Bone

Under four daily activities—sitting, standing, walking, and stair climbing—the bar chart (Figure 4.2.5) shows the maximum deformation experienced by osteoporotic and healthy femur bones. Elastic strain increased with activity level for both bone types, as was to be expected. Yet, especially when walking and climbing stairs, the osteoporotic femur continuously showed significantly greater deformation values than the healthy femur. The osteoporotic femur, for example, showed almost four times the strain of the healthy femur during stair climbing. The maximum equivalent stress (Von Mises stress) (Figure 4.2.6) values for osteoporotic and healthy femurs were measured during the same activities. When compared to healthy femurs, osteoporotic femurs continuously showed higher stress concentrations across all activities. Furthermore, the osteoporotic femur experienced a peak equivalent stress of approximately 146 MPa during stair climbing, more than four times the healthy femur's stress (33 MPa). Since osteoporotic bone is less mechanically strong, there is a significant rise in stress under high loading conditions.

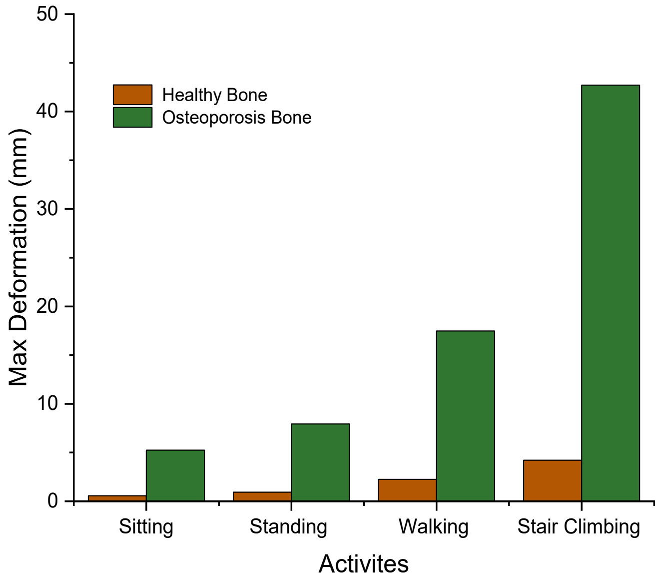

Figure 4.2.5: Comparison of Maximum Deformation Between Healthy and Osteoporotic Femur Bones During Different Daily Activities

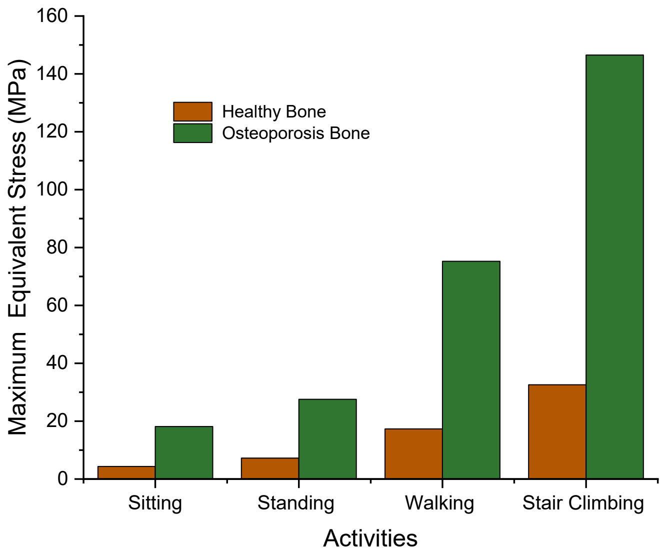

Figure 4.2.6: Comparison of Maximum Equivalent Stress Between Healthy and Osteoporotic Femur Bones During Different Daily Activities

5. Conclusion

This investigation examines the biomechanical and vibrational properties of the human femur bone, assessing how it responds in both healthy and osteoporotic conditions. The results clearly show that osteoporosis significantly affects the mechanical integrity of the femur, as evidenced by high stress levels during all activities, increased deformation, and decreased natural frequencies. Vibrational analysis in osteoporotic femurs consistently showed a 20–36% reduction in natural frequencies when compared to healthy bone, indicating a loss of stiffness and structural stability. This reduction highlights how osteoporotic bones are more vulnerable to resonance effects and dynamic instabilities, which may increase the risk of fracture while doing daily activities. Biomechanical simulations also showed that osteoporotic femurs have stress and deformation values up to four times higher than those of healthy bones, particularly during challenging activities like stair climbing. These findings directly support clinical observations of reduced load-bearing capacity in osteoporotic patients, underscoring the importance of early diagnosis and targeted intervention strategies. Overall, the combination of vibrational and biomechanical analyses provides a more comprehensive understanding of the effects of osteoporosis on femoral mechanics. The insights gained from this study can inform fracture risk assessment, rehabilitation planning, and the design of preventive measures to improve patient safety. Future work may integrate artificial intelligence and machine learning techniques to enhance predictive modeling and support personalized orthopedic care tailored to patient-specific bone conditions.

Author Contributions:

1.Md Tanvir Shahariar: Conceptualization, Methodology, Writing – original draft, Investigation, and analyses.
2.M.M. Tariqul Islam Mesbah: Data curation, Software.
3.ASM Sayem: Supervision, Writing – review & editing.
4.Rahatul Islam: Visualization, Validation All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work.

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The authors declare that they have no competing interests.

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This study did not involve human participants, animals, or clinical data directly. The femur models were reconstructed from publicly available imaging data for research purposes. Therefore, ethical approval and informed consent were not required.

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