Indonesian Journal of Electrical Engineering and Computer Science
Vol. 39, No. 1, July 2025, pp. 89~100
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v39.i1.pp89-100

Predictive modelling of osteoporosis and effect of BMI on the risk of fracture in femur bone using COMSOL Multiphysics: a computational modelling approach

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Article Info

Article history:

Received May 7, 2024
Revised Nov 30, 2024
Accepted Feb 27, 2025

Keywords:

Body mass index
Bone health
COMSOL Multiphysics
Fracture risk
Osteoporosis

ABSTRACT

This study explores the intricate relationship between osteoporosis, body mass index (BMI), and the risk of femur fractures using computational modeling. Osteoporosis is a silent metabolic disorder that depletes bone density and structure, significantly increasing the risk of fractures, particularly in weight-bearing bones such as the femur. To analyze the impact of mechanical stress on osteoporotic bones, COMSOL Multiphysics was utilized to simulate stress distribution in a femur under varying BMI conditions, providing valuable insights into how BMI influences bone health and fracture risk. A three-dimensional (3D) femur model was designed using computer-aided design (CAD) software, with specific material properties assigned for both healthy and osteoporotic bones. Finite element analysis was conducted by applying different load conditions, representing body weight, on the femur head. The results highlighted stress distribution and deformation patterns, identifying regions most prone to fracture. The findings demonstrate that while higher BMI typically correlates with increased bone density, it also leads to greater deformation in osteoporotic bones under stress, emphasizing the complex interplay between BMI and bone strength. These insights underscore BMI's critical role in fracture risk management. Future research should incorporate advanced fracture mechanics models and clinical data to enhance predictive accuracy and develop targeted strategies for fracture prevention in osteoporotic patients.

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1. INTRODUCTION

Roughly 15% of the adult human body weight comprises bone, a thick, stiff connective structure made of cells, collagen fibers, and minerals, primarily calcium and phosphate [1], [2]. The 206 bones comprising the axial and appendicular skeletons comprise the human body [3], [4]. The production of blood cells by bone marrow, support and protection of vital organs, and mobility are just a few of the many important roles that bones perform [5], [6]. Of all these vital roles, forming the human body's structural skeleton is the most significant.

Bone diseases encompass a spectrum of problems that may impact the strength, structural soundness, and general state of the bone. Numerous variables, such as age, gender, hormonal imbalance, dietary inadequacies, changes in lifestyle, genetic anomalies, can cause these illnesses [7]. Bone cancer, rheumatoid arthritis, osteoporosis, and osteoarthritis are a few of the most frequent bone illnesses [8], [9]. Pain, fractures, deformities, and a host of other issues can result from these disorders and compromise one's quality of life. Early diagnosis of bone problems can be greatly aided by diagnostic methods such as bone density evaluation, medical imaging, and blood testing [10], [11].

One of the most prevalent metabolic bone diseases, osteoporosis causes bone tissue to deteriorate and lose mass [12], [13]. This raises the possibility of fractures by making the bone brittle. Since osteoporosis does not manifest any signs until the bone fractures or cracks, it is known as a silent illness [14]. According to research, 200 million people globally may be affected by osteoporosis. Hip fractures are predicted to affect half of Asia's population by 2050, which is causing growing worry in the region [15].

Osteoporosis has several reasons, one of which is aging. As people age, their natural bone density gradually declines, which causes their bones to become fragile [16], [17]. Furthermore, because menopause speeds up bone loss, women are more likely than males to acquire osteoporosis [18], [19]. In addition, a person's family history and lifestyle decisions may increase their chance of getting osteoporosis. Osteoporosis can also result from excessive alcohol use, smoking, and nutritional deficits that compromise bone health [20]–[22]. Among those over fifty, one in three women and one in five men suffer from osteoporosis-related fractures [23]. The bone becomes weak and porous enough to break with little strain or stress when osteoporosis weakens and reduces the density of the bone. This may provide a risk to those with osteoporosis [24]. Weight-bearing bones like the femur (thigh bone), and tibia (shinbone), are susceptible to stress fractures [25].

The body mass index, or BMI, is a popular statistic for determining a person's body weight in proportion to their height [26], [27]. Reduced bone density and structural degeneration of bone tissue, on the other hand, are characteristics of osteoporosis [28]. The relationship between osteoporosis and BMI, as well as the risk of fractures, is nuanced and multifaceted [29].

The impact of body weight on bone density is one factor in the connection between osteoporosis and BMI. In general, bone mineral density is higher in those with higher BMIs. Increased body weight puts more mechanical stress on bones, which can promote bone remodeling and increase bone mass. Because of this, those with higher BMIs could be somewhat protected from osteoporosis [30].

The link is not, however, exclusively based on total BMI. One important factor is how body fat is distributed. Increased BMI is frequently linked to excess belly fat, which may be detrimental to bone health [31]. An imbalance in the molecules that adipose tissue generates can affect bone metabolism and potentially lead to a reduction in bone density [32], [33].

The interaction of several variables also affects the association between fracture risk and BMI. Because of their greater bone density, those with higher BMIs may be somewhat more resistant to fractures, but bone tissue quality is just as vital. In certain situations, people with higher BMIs may still be at risk for fractures if there is a structural defect in their bones, such as poor bone quality or certain medical disorders [34].

The longest and strongest bone in the human body is the femur, sometimes referred to as the thigh bone. It is a weight-bearing bone that contributes to shock absorption by allowing the leg to move freely and shield surrounding tissues and joints from severe impact. Additionally, it is a significant location for the attachment of several vital muscles that support stable leg movement [35], [36]. Figure 1 depicts the anatomical structure of the femur.

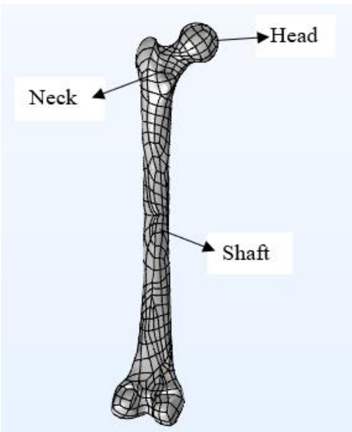


Figure 1. Anatomical structure of femur in human

An increasing number of older people, particularly those with osteoporosis, suffer fractures in the proximal femur, which is situated close to the hip joint. These fractures fall into two main categories: femoral neck fractures, which involve the femur's neck, and intertrochanteric fractures, which happen between the greater and lesser trochanters [37]. Surgical intervention is frequently necessary for proximal femur fractures to accurately realign and stabilize the fragmented bone pieces, promote efficient healing, and restore functional abilities.

An excessive build-up of body fat, or obesity, introduces a complicated interaction of variables that affect the risk of fracture in osteoporotic femur bones. Obesity, ironically, is linked to negative impacts on bone quality and bone metabolism, even if larger body mass can have some protective benefits on bone density through increased mechanical stress [38]. Obese people's increased weight on weight-bearing bones, including the femur, may cause changes in bone structure, such as an increase in bone mineral density. However, this seeming benefit is offset by the negative consequences of obesity-related conditions, such as persistent inflammation and hormone abnormalities, which worsen the damaged bone microenvironment. Furthermore, the way body fat is distributed, especially visceral fat, might result in the production of inflammatory chemicals that could harm bone health [39].

The biomechanical effects of obesity also need to be taken into account. Being overweight can put the femur under increased mechanical stress, which may be more than the bone's regenerative ability, particularly in those who already have osteoporosis. An increased incidence of femur fractures may result from this increased mechanical strain as well as the poorer bone quality linked to fat. Because of this, the relationship between obesity and the risk of fracture for osteoporotic femurs is complex, having a mix of favorable and unfavorable effects on bone health. To enhance bone health and reduce the incidence of femur fractures, it is imperative to comprehend this complexity to create tailored therapies that meet the unique problems given by obesity in persons with osteoporosis.

Despite previous research highlighting the association between osteoporosis, BMI, and fracture risk, current computational models lack precise predictions of fracture locations in osteoporotic femurs under varying BMI conditions. Prior research shows that higher BMI is often associated with increased bone density due to mechanical stress; however, excessive adiposity and fat distribution may adversely impact bone quality. This study aims to bridge this gap by utilizing COMSOL Multiphysics to model the femur bone under mechanical stress, providing detailed insights into how BMI influences fracture risk. The study's goal is to better understand the relationship between bone health, BMI, and osteoporosis, focusing on identifying high-stress regions in the femur susceptible to fracture.

This paper builds on existing works by integrating computational modelling with clinical observations to predict the risk of fracture in osteoporotic femurs. The findings are expected to aid in the development of tailored treatments and preventative measures for individuals at risk of osteoporosis-related fractures. The paper is structured as follows: first, the methodology is described in detail, followed by the presentation of simulation results, which are then discussed in relation to current research. The conclusion summarizes key findings and suggests directions for future research.

2. METHOD

The primary objective of this study is to assess the fracture risk in osteoporotic femur bones by simulating mechanical stress using COMSOL Multiphysics. COMSOL Multiphysics was chosen for its capacity to model the complex mechanical behavior of bones under stress and to simulate fracture risks accurately. The model's integration of material properties such as young's modulus and poisson's ratio allows for realistic simulation of osteoporotic conditions. This computational approach predicts stress distribution in the femur under various load conditions, focusing on the influence of BMI on bone strength. The model provides a detailed understanding of how external forces contribute to bone deformation and potential fracture sites in osteoporotic individuals.

2.1. Geometric design

The study began with the creation of a two-dimensional (2D) femur model, which was converted to a 3D representation through volume rendering in COMSOL Multiphysics. The femur geometry was imported into the software shown in Figure 2, and all necessary parameters, such as bone dimensions and mechanical properties, were added to accurately simulate an osteoporotic bone.

2.2. Material properties

The material properties of both healthy and osteoporotic bones were applied. A healthy bone has a young's modulus of 16.5 GPa, a poisson's ratio of 0.43, and a density of 2,000 kg/m³ as shown in Table 1. However, osteoporotic bones, characterized by a decrease in rigidity, were assigned different properties shown in Table 2. These differences were incorporated into the entire femur geometry to accurately reflect the reduced strength and increased porosity of osteoporotic bones as shown in Figure 3.

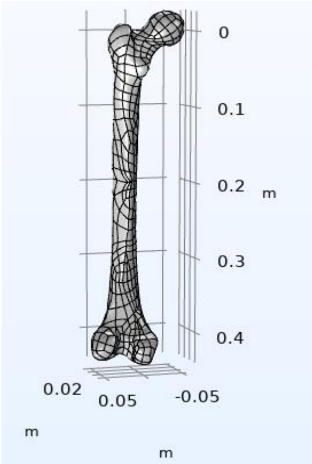


Figure 2. A 3D model of the femur in COMSOL Multiphysics

Table 1. Material properties of a healthy bone

Properties	Value	Units
Young's modulus	16.5	GPa
Poison's ratio	0.43	1
Density	2,000	Kg/m^3

Table 2. Material properties of an osteoporotic bone

Properties	Value	Units
Young's modulus	11.5	GPa
Poison's ratio	0.2	1
Density	800	Kg/m^3

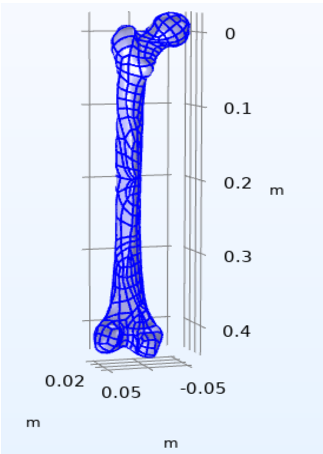


Figure 3. Material applied to entire geometry

2.3. Physics type

The "Solid mechanics" physics module was utilized to analyze stress distribution and structural integrity under mechanical loading. This module is crucial for understanding deformation and failure points in bones subjected to high stress. Using this physics, the model simulates the impact of different force magnitudes on the femur, incorporating tools for fracture mechanics and damage accumulation.

2.4. Meshing

To enhance the simulation's accuracy, the femur geometry was meshed into smaller finite elements, allowing for detailed analysis of stress and deformation patterns. An extra-coarse mesh was applied for computational efficiency while maintaining adequate resolution. This meshing allowed us to strike a balance between accuracy and the computational cost of the simulation. The mesh of the geometry is shown in Figure 4.

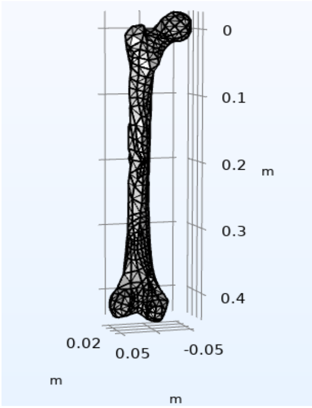


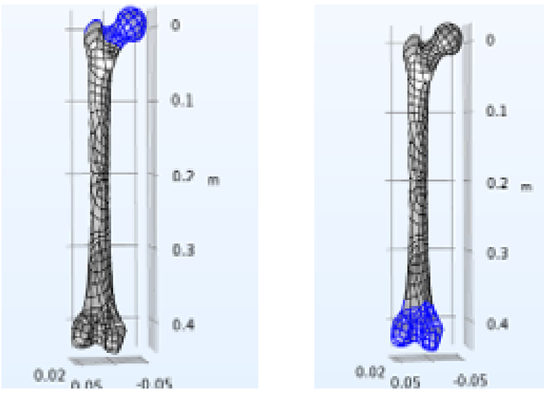
Figure 4. Extra coarse mesh applied to femur geometry

2.5. Applying the load

The femur bone which is also known as the thigh bone, is located in the upper portion of the leg. It connects the hip joint to the knee joint. The proximal end of the femur is attached to the hip joint while the distal end is attached to the knee joint. The femur is a critical load-bearing bone that facilitates movement and supports body weight.

The femur is subjected to mechanical forces associated with body weight. As the body weight increases, the magnitude of load on the femur's head increases which can impact its stress distributions. Osteoporosis is a disorder that makes the bones porous and brittle and they become more sensitive to load-bearing activities. Therefore, people having a BMI value greater than 30 are considered to be obese and are more likely to develop osteoporosis. Their bones are subject to higher mechanical loading due to their weight.

A normal femur bone can adhere to a weight equal to 30 times the normal body weight but an osteoporotic bone can bear lesser weight and is more likely to crack or have increased fracture risk. A static load of approximately 2,000 N was applied to the head of the femur, simulating the effects of body weight on the hip joint shown in shown in Figure 5, where Figure 5(a) illustrates the applied boundary load on the femur head and Figure 5(b) shows the fixed distal end of the femur. The distal end of the femur was fixed to prevent articulation, ensuring that any deformation and stress occurred solely due to the applied load.



(a) (b)

Figure 5. Boundary conditions of the femur model (a) boundary load of ~2000 N applied at the femur head to simulate body weight and (b) the distal end of the femur is fixed to prevent movement and ensure stress develops solely from the applied load

This boundary condition enabled the observation of stress distributions and potential fracture sites in osteoporotic femurs under different load magnitudes. The effect of BMI on fracture risk was also analyzed by simulating various body weights, showing how increased load on the osteoporotic femur increases the risk of fracture shown in Figure 6. The force applied to the femur is influenced by body weight, intensity of physical activities performed as well and any external forces acting on it. The load is considered a static load and the inclination angle is 0 degrees. The femur being a strong bone is designed in a way that it can withstand forces associated with various activities like walking, running, and jumping.

An osteoporotic femur becomes brittle enough that it can deform easily once it is subjected to load and the risks of fracture are much greater as compared to normal bone. Therefore, people suffering from Osteoporosis need to keep an eye on their BMI. People having more than normal body weight are more susceptible to developing fractures in their bones.

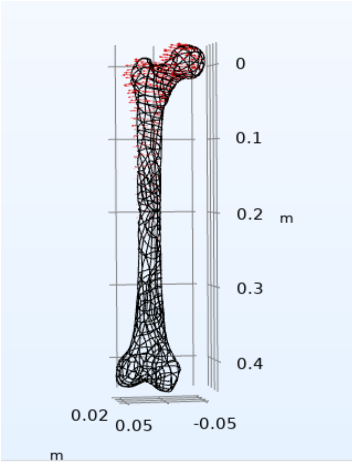


Figure 6. Forces are applied to the head of the femur

2.6. Finite element analysis

For the structural analysis of the osteoporotic femur and to analyze its behavior when it is subjected to load, it is divided into finite elements. The stress was applied on the head of the femur and the displacement is shown in Figure 7. The most stressed area can be shown in red color which is the head while the proximal end has the least stress which is shown in blue color. In this analysis, a range of loads were applied to the head of the femur, and maximum stress sites were observed. These sites are at an elevated risk of developing fractures in the future.

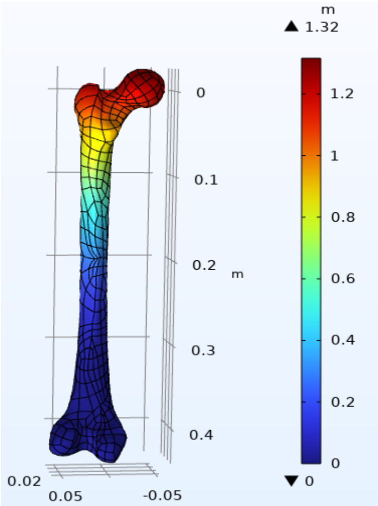
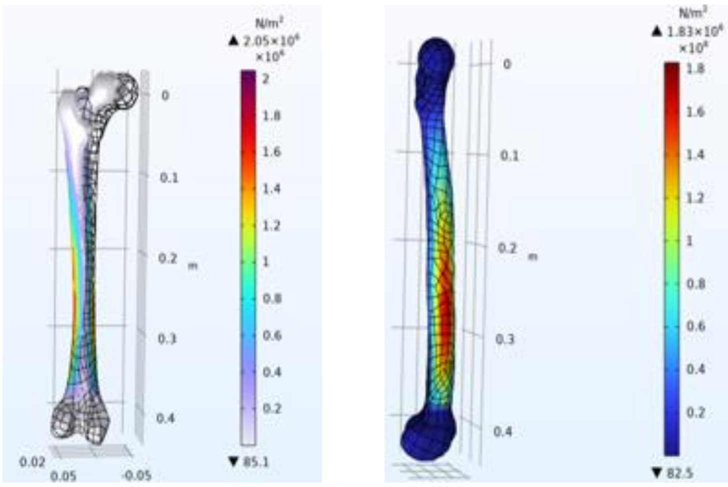


Figure 7. Finite element analysis

2.7. Deformation and maximum stress site

The deformation of the femur bone when approximately 200 kg of load is applied is shown in Figure 8. Specifically, Figure 8(a) illustrates the deformation under load, while Figure 8(b) highlights the resulting stress concentration. When the load is applied to the femur's head, the maximum stress is observed in the shaft which is shown by the red color in the shaft of the bone as shown in Figure 8(b). This shows that the shaft of the femur is more prone to developing cracks when load is applied.

As depicted in Figure 9, a contour plot was generated to visualize stress distribution across the femur. Red areas indicate high stress, primarily concentrated at the femur's head and shaft, while blue areas represent regions of lower stress. These findings suggest that the femur's shaft is particularly vulnerable to fractures when exposed to excessive loads, especially in individuals with reduced bone density.



(a) (b)

Figure 8. Finite element results of femur under static loading (a) deformation observed when 2,000 N is applied to the femur head and (b) stress concentration visualized primarily along the femoral shaft

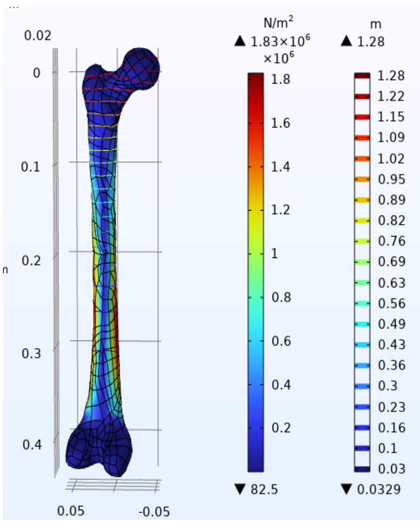


Figure 9. Contour plot

3. RESULTS AND DISCUSSION

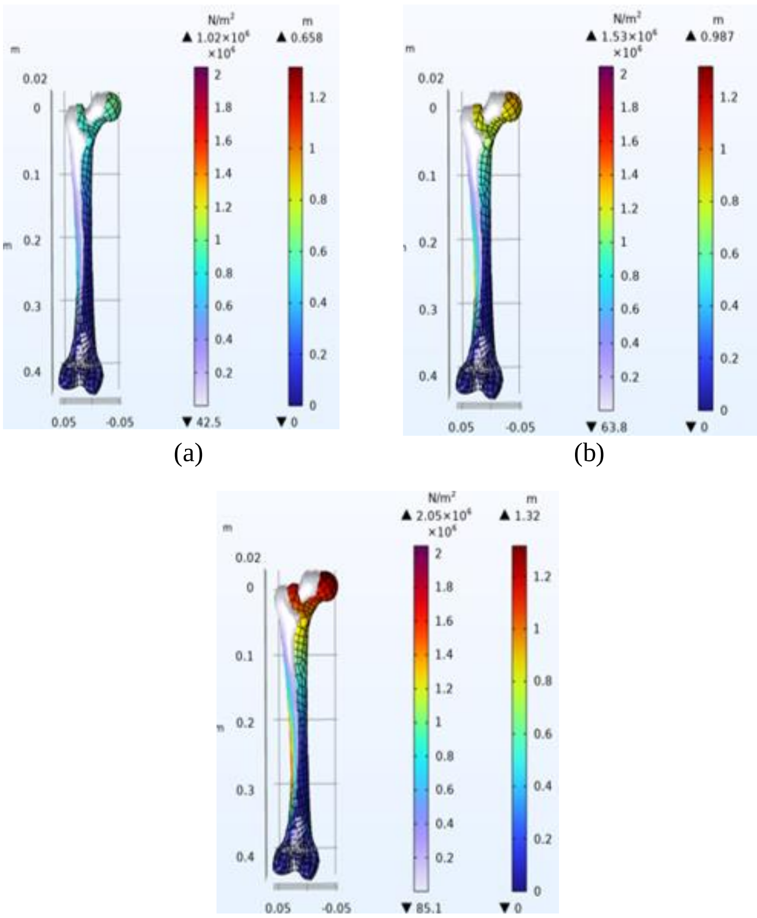
When an external force is applied to an osteoporotic femur, the resulting deformation patterns are critical in determining high-risk areas for fracture. Our simulations revealed that under a load of approximately 2,000 N, the femur exhibits significant deformation in the shaft region, which corresponds to the highest stress concentration. This result aligns with clinical observations of fractures typically occurring in this region among osteoporotic patients.

When force is applied to an osteoporotic femur, the deformation is noticeable. This information shows areas that are subjected to higher strain. The deformation magnitude can help determine the risk of fracture in the future. The difference is visible when forces between 1,000 N (approximately 100 kg) to 2,000 N (approximately 200 kg) are applied as shown in are applied as shown in Figure 10, which includes subfigures 10(a), 10(b), and 10(c) corresponding to deformation under 100 kg, 150 kg, and 200 kg loads, respectively.

It is quite clear from the findings that when an osteoporotic femur is subjected to increasing force, we observe a corresponding increase in its deformation, primarily manifesting as bending. This is where things start to get interesting but also worrying: there is a tipping point at which the bone can no longer bear the strain, depending on its density, strength, and mineral content. Contrary to the assumption that higher BMI protects against osteoporosis, the simulation demonstrated that increased weight leads to a higher risk of fractures due to localized stress in specific bone regions. Depending on the general health of the bone, this threshold changes from one to the next.

Interestingly, when forces were gradually increased from 1,000 N to 2,000 N, the deformation magnitude showed a linear relationship with the applied force as shown in Figure 11. This indicates that osteoporotic femurs, though less dense, still follow predictable mechanical behavior patterns under stress. However, the threshold at which these bones fracture is significantly lower compared to healthy bones.

The results contrast with studies that suggest higher BMI offers some protection against fractures due to increased bone mass. The findings, however, highlight the counterproductive effects of high BMI when paired with osteoporosis. Although elevated BMI may increase bone density, the mechanical stress from additional body weight exacerbates fracture risk due to compromised bone quality in osteoporotic individuals.



(a) (b)

(c)

Figure 10. Deformation of the femur under varying static loads: (a) under 100 kg load, minor displacement is observed mostly in the femur head, (b) under 150 kg load, moderate deformation extends to the shaft, and (c) under 200 kg load, significant stress is distributed along the shaft and femur head, indicating higher risk of structural failure

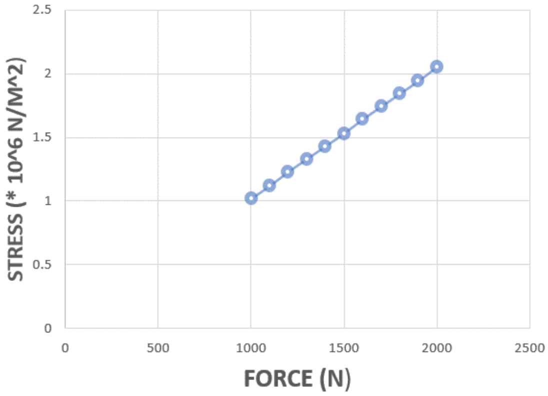


Figure 11. Linear relationship between force and stress

4. CONCLUSION

The study used COMSOL Multiphysics to simulate the effects of BMI on osteoporotic femur strength and fracture risk. The results emphasize the importance of considering BMI in fracture risk assessments, particularly in patients with osteoporosis. While higher BMI can increase bone density, it also leads to stress concentrations that may increase fracture risk. Future studies should integrate advanced fracture mechanics to improve the model's predictive capabilities. Collaborations with clinicians to validate the model's accuracy through clinical data would enhance its practical applicability. Incorporating imaging techniques like computed tomography (CT) scans could refine the bone's geometrical representation, further improving fracture risk prediction.

ACKNOWLEDGMENTS

The authors, with regard to the consent taken, sincerely acknowledge the valuable insights and guidance provided by Engr. Touseef Yaqoob from the Intelligent Systems Research Lab, United Kingdom, throughout the development of this research. His expertise and constructive feedback greatly contributed to refining the conceptual framework and technical aspects of this study. We are grateful for his continuous support and encouragement, which played a pivotal role in enhancing the quality of this work.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aleena Kamal	✓		✓	✓				✓	✓				✓	
Minahil Kamal		✓						✓	✓		✓	✓		
Mashal Fatima	✓		✓	✓					✓		✓		✓	
Syed Muddusir Hussain					✓		✓			✓		✓		✓
Jawwad Sami Ur Rahman						✓				✓				
Sathish Kumar Selvaperumal					✓					✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Sathish Kumar Selvaperumal, upon reasonable request.

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