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Design and Fabrication of a 3D-Printed Femur Model: Insights into Mechanical Properties and Implant Research

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Abstract

This study is an attempt to analyse the 3D printing of the female femur model of the central India region and provides ample suggestions for bone implant research. This article discusses the design development and experimental validation of finite element analysis (FEA) results with the 3D-printed bone model. Using CT scan data, the FE analysis is executed on a real femur bone of a 25-year-old female of 52 kg weight with heterogeneous material characteristics and physiological loading conditions. The femur bone model is fabricated using a cost-effective 3D printer, fused deposition modelling (FDM), with a filament spool of polylactic acid (PLA). Compression tests were conducted on the fabricated PLA femur-bone model derived from a CT scan, providing insights into its mechanical behaviour under a specific load of 510 N. The total deformation during the FE analysis and compression test of the 3D printed model was 1.339 mm and 1.558 mm, respectively. The results show a strong relationship between porosity, mechanical strength, and chemical and biological stability, which is crucial for patient-specific modelling (PSM), designing medical implants and understanding implant and injury mechanisms.

Keywords: Femur, finite element analysis, 3D printing, FDM, patient-specific modelling, implants design

INTRODUCTION

Biomechanical systems and structures can be studied and modelled using concepts and principles from physics [1]. Bones are the hard tissues that protect the body, support loads, produce red blood cells, white blood cells, store minerals, and provide body structure and support to enable movement[2,3]. The femur is the longest bone in the human body that links the hip and knee joints. Running, jumping, walking, and standing are some of the activities that are vital for the human body [4]. It is only powerful when compressed [5]. Different kinds of trauma can damage the femur, causing it to fracture into two or more pieces. This might happen to the part of the femur head, the femur shaft, or the condylar part of the femur [6]. Therefore, a bone implant is a medical technique developed to replace a missing joint or to support a fractured bone. In interdisciplinary research, femur bone is frequently used in orthopaedic surgery, biomechanical engineering, biomedical engineering, rehabilitation, and medical implant technologies[7]. Several considerations, including age, gender, bone mineral density(BMD), location, cost, ethical concerns, and the lack of bone samples, must be considered while accomplishing human femur bone analysis for implant design and production. Consequently, the study's outcome is nonconformity, and the experimental waiting time is prolonged [8].

Over the last three decades, researchers have developed various techniques to simulate femur

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bone using cadaveric, synthetic, dry bones, etc. [9]. High-speed computing, developments in imaging technologies and advances in numerical methods have made patient-specific modelling (PSM) for optimising clinical treatments viable. Finite element (FE) analysis is the most popular approach for computer simulation. Input FE models require accurate characterisations of the geometry, material properties, loading conditions and interactions. Each character has strong patient-specific elements that need to be addressed[10].

3D printing is a perfect technology for manufacturing implants and medical devices. The major reasons are low-cost additive manufacturing and that the medical implant producers have great independence in designing new implants and prototypes, allowing them to customise new medical implants based on the market's needs in a much shorter time. Medical 3DP was once imagined to be a dream project. But time and investment brought it to reality. Today, 3D printing represents a huge specific implant, enabling the opportunity for pharmaceutical or healthcare companies to help create more rapid production of medical implants and change the way doctors and surgeons plan procedures [11,12].

For customised human bone implants, three-dimensional printing is often used. Rapid Prototyping (RP) is also known as three-dimensional (3D) Printing techniques or additive manufacturing (AM) technology, is a scientific advance that creates models out of 3D software systems (CAD). Unlike the subtractive method, where the material is removed to fabricate the product, 3D printing (3DP) relies on an additive-level correlation method that adds a material layer by layer to build a complete model. Since it takes a long time to make models, moulds, and prototypes in the production field, and some other complicated processes are used to reduce the production time. The manufacturing industry has initiated 3D printing victimisation technology to provide exquisite models, moulds, and prototypes [13]. In the subtractive method, tool movements are intended for material removal from the workpiece to achieve the specified form. Compared to subtractive methods like turning and machining, 3DP has the greatest capability to induce complicated geometries like anatomical structures. 3DP provides cost-effective models of the styles that will be used to understand the product before the fabrication process of high-priced prototypes. 3D techniques include stereolithography (SLA), Selective Laser Sintering (SLS), Fused-Deposition Modelling (FDM), and Laminated Object Manufacturing (LOM)[14]. The FDM technique is preferred for the current work, as mostly strong polymers can replicate the femur bone and are easily available.

Due to human biological problems like osteoporosis, cancer or rupture injuries, actual bones are replaced by synthetic or customised patient-specific implants. Optimal bone implant design is a critical issue [15,16,17]. Various biological materials, i.e. Steel, Titanium (Ti), Polymers etc. are used as implant material. Ti alloys are the preferred option in long-term load-bearing osseointegrated bone implants due to a combination of relatively low elastic modulus, good bio-compatibility, exceptional corrosion resistance, and suitable fatigue strength when compared with other biomaterials such as cobalt alloys, steels and polymers (PMMA, PEEK)[18,19]. However, the stiffness of solid Ti alloys is higher than that of bone, leading to a stress-shielding phenomenon: when there is a mismatch in rigidity between the implant and the surrounding bone, the implant bears most of the load and reduces stress transfer to the bone [20]. Bone resorption is an undesirable consequence of the absence of long-term strain stimulation in the bone[21,22,23].

Polycarbonate is also broadly used in 3D printing owing to its good strength and stiffness properties [24,25].PEEK materials are used in various surgical and medical fields[26,27]. Lately, carbon-fibre-reinforced 3D-printing filaments have been introduced into the bio-medical field as carbon fibre provides an increase in strength and mechanical properties of the filament[28]. Carbon-fibre-reinforced PEEK has recently been used in orthopaedic implants such as knee and hip replacements and bone plates [29]. So far, the most widely used polymer filaments are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA)[30]. PLA filaments have a better prospect than ABS because they are perishable, bio-absorbable, and renewable thermoplastic polyesters with great mechanical strength and method ability [31,32].

Implant design is affected by human anatomy, age, sex, bone mineral density and geographical location. In India, human anatomy varies from north to south and east to west. Femur CT scan data referred by a physician is used for femur modelling and fabrication[33,34].

The femur, the longest and strongest bone in the human body, differs between males and females due to genetic, hormonal, and biomechanical influences. In females, the femoral neck angle is typically wider (127–135 degrees) compared to males (120–130 degrees), accommodating a broader pelvis essential for childbirth. Males generally have a larger femoral head, enhancing load-bearing capacity and joint stability, whereas females have a smaller femoral head, potentially increasing the risk of hip instability. Additionally, the male femoral shaft is thicker and more robust, with greater cortical thickness, making it more resistant to bending and torsional forces. In contrast, females have a more gracile femoral shaft with thinner cortical bone. Males also have higher bone density, reducing fracture risk, whereas females are more prone to osteoporosis. The larger femoral angle in females, due to their wider pelvis, influences gait and movement patterns. These anatomical variations are crucial for understanding human biomechanics and optimizing implant design[35].

There is a lot of research going on right now in the field of orthopaedic implants. There are many computerised methods for analysing the femur bone, but the experimental analysis needs real people or animal specimens. Despite the plenty of research in finite-element simulations and 3D modelling of the femur, this paper focuses on the customised implant design for females of the central India region using the FDM technique and provides ample suggestions for bone implant research. This research will help in designing PSM and customised female femur bone implants

MATERIALS AND METHODS

This article aims to use the CT scan data of the real female femur bone to simulate the solid model of the femur using FEA and validate the results by fabricating a femur-bone model with the nearest similar property to the human femur using FDM. The major task is to print correct three-dimensional female femur bone specimens that are to be tested to understand the experimental/numerical correlation. CT scan, MIMICS Software, ANSYS WORKBENCH® 2021, and Cura 5.9.1 slicing software are used. This study was carried out in four distinct stages:

a. *3D solid modelling*: Creating a detailed model of the femur bone using CT scan data.
b. *Finite element analysis (FEA):* Developed a finite element model and simulated the femur's behaviour.
c. *3D printing*: Fabricated a physical model of the female femur using PLA material.
d. *Experimental validation*: Conducting experiments on the 3D-printed model to verify the FEA results pattern.

Solid Modelling of Femur Using CT Scan

A non-invasive and non-destructive CT scan data of the real proximal femur of a 26-year-old female from central India is collected in the form of a digital imaging and communications in medicine (DICOM) file. The high-resolution multi-slice CT Scanner (SIEMENS Sensation, 40 Slice, Recon 1.5 mm) was utilized to accurately characterise the bone geometry and density distribution with a total of 343 images with a slice thickness of 0.4 mm. Data obtained from the DICOM file images are being converted into solid models in Materialise MIMICS 21 (Version 21; Materialise NV, Leuven, Belgium) in the ICT lab IIITDM Jabalpur, India. Multiple tools, including thresholding, editing mask, region growing and 3D mask computation, are being used to create the 3D solid model. Further, this 3D solid model is being exported for FE analysis and fabrication of femur bone using 3DP techniques FDM.

FE Analysis

The Finite Element Analysis (FEA) of the human femur bone is an interesting field that combines engineering principles with medical applications. Image-based modelling techniques, such as computed tomography (CT) scans, allow us to create three-dimensional finite element models of the femur bone that incorporate bone geometry and density information to simulate mechanical behaviour under different loading conditions. The CT scans are commonly used to generate accurate FE models for predicting biomechanical properties, stiffness, strength, and deformation behaviour. These properties are essential for understanding bone health, designing implants, and assessing fracture risk.

Pre-Processing

A 3D model is being created from the segmented DICOM images and sent to 3-Matic Research for additional pre-processing. Here, a surface mesh and a volumetric mesh are generated for further FEA, comprising 76265 nodes and 340786 elements, respectively. Through volumetric meshing, four-node linear tetrahedron elements (C3D4) are developed from the surface mesh's triangular elements, as shown in Figure 1. These volumetric mesh models are again exported to MIMICS for material assignment.

The femur is a quasi-brittle substance composed of cancellous and compact bone, with a complex structure. It is referred to as an isotropic material in some contexts and an anisotropic substance in others [36]. The Hounsfield Unit derived from the CT scans is related to the mechanical characteristics of bone taken into account in the numerical model. Due to the dependence on age, gender, health, nutrition, and other parameters, there is a broad variation of mechanical characteristics of the human femur. Grey values are calculated for assigning heterogeneous material properties using the empirical relationship between Grey values, Young's modulus, and Density. Young's modulus and density will be expressed as: Density = 13.4 + 1017 × Gray value. Density = -388.8 + 5925×E-Modulus [37,38].

Computational Solving

After completing the meshing and material assignment, as shown in Figure 2, the three-dimensional model of the femur bone was imported into the structural workbench, followed by the FE modeller for static analysis. The entire finite-element computations were made using the ANSYS WORKBENCH® 2021 software package. In the structural workbench, boundary conditions were applied to the female femur, similar to the loads acting on the real human femur while standing. The boundary conditions shown in Figure 3 are considered by fixing the lower end of the femur model, and a compressive load is given on the head of the femur. A compression-type load of 52 kg is applied on the femur head with an angle of 28 degrees [38].

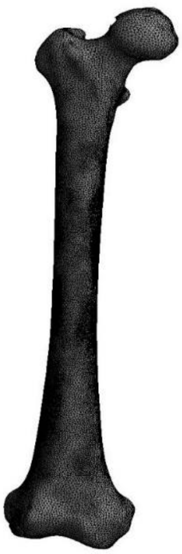

Figure 1. Solid model of femur bone with surface mesh.

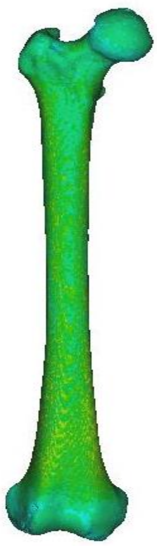

Figure 2. Femur bone with material properties.

Figure 3. Femur bone with boundary conditions

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Table 1. FE Analysis parameters and results of femur bone.

Parameters	Values
Age group (in Years)	25 years
No of images	343
Weight (kg)	52
Total number of nodes	76265
Total number of elements	340786
Total Deformation (mm)	1.399
Maximum Principal Stress (MPa)	75.21
Von- Mises Equivalent Stress (MPa)	76.05

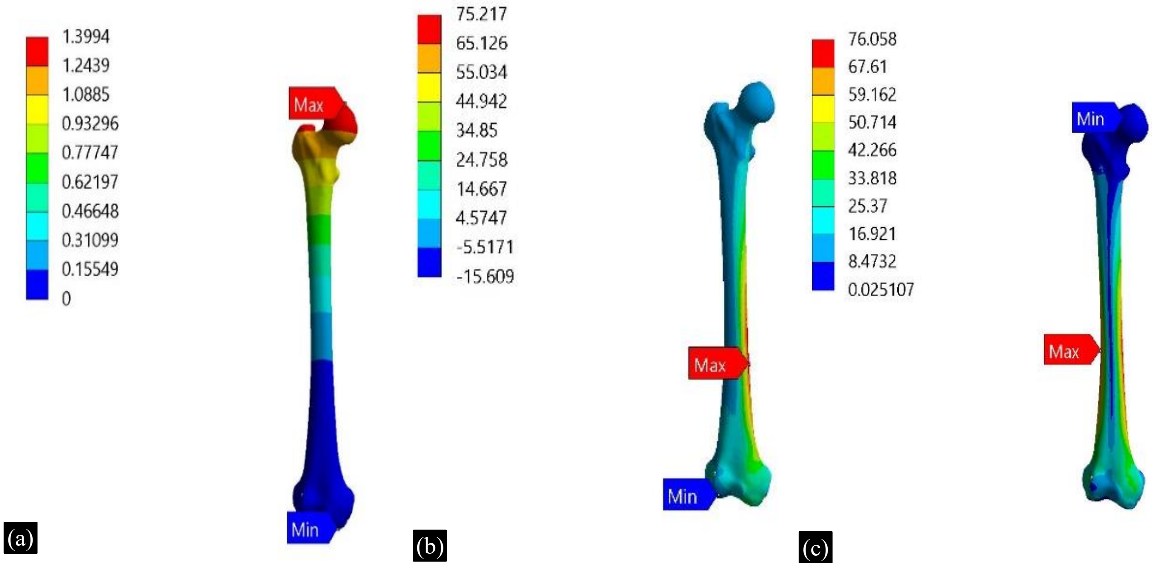

Figure 4. Femur bone with FE analysis (a) Total deformation, (b) Maximum principal stress, (c) equivalent Von–mises stresses.

Post-Processing

The post-processing capabilities of ANSYS® were utilised for generating the Equivalent Stress and Total Deformation for the human female femur bone with realistic loading conditions and heterogeneous material characteristics. A detailed post-processing result was generated in the FE analysis. Various parameters used in the FE analysis are shown in Table 1. The finite-element method results of the total deformation, the maximum stress, and the equivalent stress of the female femur bone model are shown in Figure 4.

Fabrication of 3D Printing Model

The femur design was too intricate and challenging to fabricate using conventional methods of manufacturing; thus, 3D printing was selected. The CT scan data in the.stl format is imported in Cura 3D printing software to design and fabricate the femur model. The femur model was fabricated using 3DP technology a Fused Deposition Modelling (FDM), with a Polylactic Acid (PLA) filament spool. FDM is a method of 3D printing in which layers of materials blend in a pattern to fabricate an object [39]. The Creality CR-10S5 500 mm×500 mm ×500 mm Large Print Size FDM 3D printer was used because of its larger bed size. Using the FDM technique, the layers of PLA were deposited layer by layer from the model obtained using the Cura software. The huge time taken for the fabrication of the female femur model with 100 % infill density. The cross-sectional area of the female femur is 100.1mm x 78.1mm x 412.5 mm.

Table 2. Mechanical and manufacturing parameters of 3DP model of the femur using FDM.

Parameters	Typical values	Parameters	Typical values
Material	Polylactic Acid (PLA)	Layer height	0.2
Density	1.24g/cm^3	Printing speed	35mm/sec
Printing Temperature	205-215^{0}C	Nozzle temperature	210 degree
Shrinkage	0.10%	Bed temperature	60 degree
Nozzle diameter	0.4 mm	Infill percentage	100%
Filament diameter	1.75mm	3D printer Chamber temperature	Room temperature

Figure 5. 3D printed femur bone with PLA material using FDM.

Figure 6. Compression test on 3D-printed PLA femur model.

The 3D printer fabricated the PLA-based femur model, featuring a single extruder, a layer resolution of 0.1–0.5 mm, and a 0.4 mm extruder nozzle diameter. The extruder nozzle operates at 210°C, while the build plate maintains a temperature of 60°C. The strong bonding between layers was achieved due to the controlled temperature, ensuring that each newly deposited layer adhered well to the previous one. This ensured high mechanical strength and structural integrity, preventing flexible deformation in the final 3DP femur model. The 3DP female femur bone shown in Figure 5 is fabricated with the following material properties and manufacturing parameters as shown in Table 2.

Experimental Setup

The 3D printed female femur bone specimen is mechanically tested to study the experimental/numerical correlation. Compression tests were performed on the cylindrical 3D-printed femur bone specimen using a computerised universal testing machine as shoen in fig 6. The compression test on the femur is a biomechanical test used to evaluate the strength, stiffness, and failure characteristics of the femur under axial loading conditions. This test is crucial in orthopaedic research, implant design, and understanding bone fracture mechanics. The frame has compression grips and SiC disc anvils to transfer the load from the specimen to the grip fixture. The load capacity of the testing machine is 100–2000 kN, and the displacement resolution is 0.01 mm. It is aligned to ensure that axial compression is applied along its longitudinal axis. The experimental compression test with a vertical

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load applied to the femur-bone model from the top of the femoral head is shown in Figure 6. The force is increased until the bone reaches its fractures. The results were obtained from the data acquisition system provided with the machine.

RESULTS AND DISCUSSION

This study focuses on the design, development, and experimental validation of Finite Element Analysis (FEA) results for the human female femur bone. In the human body, bones are supported and constrained at the joints by muscles and ligaments, which limit certain degrees of freedom. However, most modeling and in vitro experimental studies do not account for the contribution of these soft tissues. [10]

FE Results

The finite element analysis of the femur bone was performed on real female femur bone with heterogeneous material characteristics and actual physiological loading conditions. The Total Deformation of 1.399 mm, Maximum Principal Stress of 75.21 MPa and Von- Von-Mises equivalent Stress of 76.05 MPa are evaluated by numerical simulation using the finite element method as shown in Figure 4.

Compression Test Results

The 3DP femur bone model is based on CT images of a real human female femur bone with varying bone density. The 3D printing process utilized a cost-effective fused deposition modelling (FDM) 3D printer and PLA filament. Varying cortical thickness and mechanically calibrated 100 % infill density were employed.

From the visual inspection, the fabricated femur-bone model had good strength and stiffness, with a considerable degree of elasticity. Compression tests were conducted on the fabricated PLA femur-bone model shown in Figure 6, is the same boundary conditions applied in FEA. This stress-strain curve provides insights into the mechanical behaviour of the 3DP female femur bone model under a specific load of 510 N. This linear portion of the curve indicates that the material behaves elastically. The femur model shows an initial linear elastic response, followed by some non-linearity and exhibits a sudden drop in load. The failure occurred in the middle portion of the femur model, which is called a transverse fracture in orthopaedic terminology. The result obtained from the FE analysis, the maximum stresses found at the middle of a femur shaft of the 3D solid model, are similar to the transverse fracture that occurred in the 3DP implant model in the same region.

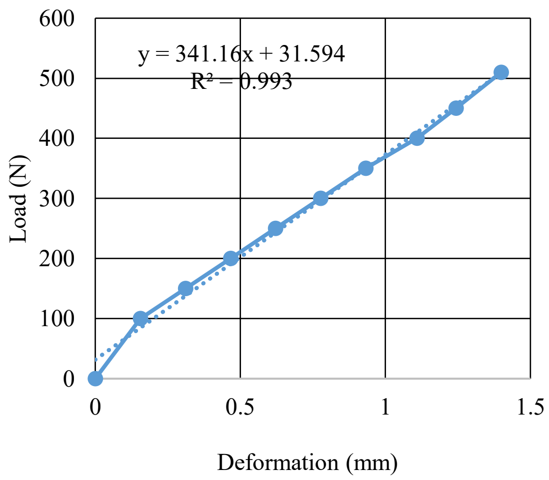

Figure 7. Deformation graph of FE model of femur bone at 510 N load

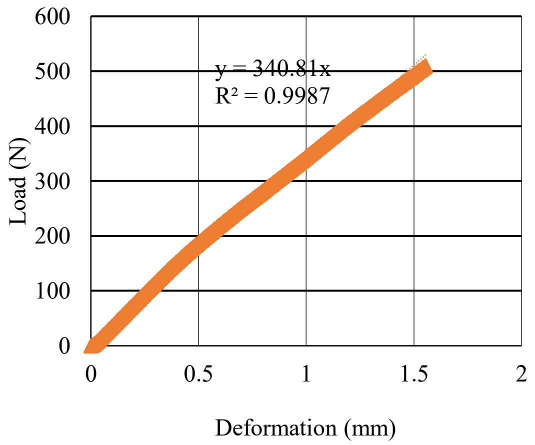

Figure 8. Deformation graph of 3D printed femur bone at 510 N load

The total deformation that occurs in the femur during the FE analysis and compression test of the 3D printed model is 1.339 mm and 1.558 mm, respectively. The deformation results are closely matched and show a nearly 10.75 % difference. Figures 7 and 8 depict the Deformation Graph of the FE model of the Femur bone and the Deformation Graph of the 3D Printed Femur Bone at 510 N load, respectively.

The deformation vs load Graph of the FE model and 3D printed bone model of the femur plotted indicates the dotted line on the graph shows a steep, almost linear increase, indicating that as the load increases, the deformation of the femur bone also increases proportionally. The linear equation $y = 341.69x + 31.594$ represents the relationship between the load applied to the femur bone and the resulting deformation. The graph shows a coefficient of determination $R^2 = 0.993$, which is very close to 1, suggesting that the FE model's predictions of deformation based on the applied load are highly accurate. Similarly, the equation $y=325.42x+15.975$ represents the relationship between the load applied to the femur bone and the resulting displacement. The graph shows an $R^2=0.997$, which is very close to 1, suggesting that the 3D-printed femur bone model's predictions of displacement based on the applied load are highly accurate. The high R^2 value indicates that the model used to create this graph is very reliable for predicting deformation in response to applied loads, which is crucial for designing medical implants and understanding injury mechanisms in both cases. The results show a strong relationship between porosity, mechanical strength, and chemical and biological stability, in are of great importance.

CONCLUSIONS

Human bone is very complex and anisotropic, with its anatomy and mechanics varying based on gender, age, and geographical location. This complexity means that studying bone can yield significant insights as each region exhibits distinct material characteristics. In this study, a solid model of a human female femur was successfully created using CT scan data for finite element (FE) analysis and experimental evaluation of a 3D-printed bone model made from PLA material. The main objective was to simulate the femur under static loading conditions using non-linear FE analysis and validate the results by fabricating the model via fused deposition modeling (FDM).

The FE analysis indicated that maximum stress occurs in the middle of the femoral shaft, a finding that was corroborated by the experimental compression test of the 3D-printed model, which also showed transverse failure in the same region. The total deformation measured in both analyses differed by only 10%, and with an R^2 value close to 1, there is a strong correlation between the two sets of results. This validation suggests that PLA-based implants are a promising choice for human bone replacement due to their favourable physical, mechanical, and chemical properties.

FE analysis of the femur not only provides valuable insights into its mechanical behaviour and fracture risk but also has significant clinical applications. As technology progresses, we can expect even more precise, patient-specific models that will enhance orthopaedic treatments and implant designs. Moreover, the versatility and cost-effectiveness of 3D printing have revolutionized the manufacturing of medical implants and devices, enabling tailored solutions that meet specific patient needs efficiently. This technological advancement is transforming surgical procedures and patient care by facilitating the rapid production and customization of implants.

Conflict of Interest

All authors involved in this work declare that they have no conflicts of interest that could potentially bias the presented findings.

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Credit Author Statement

Raji Nareliya Mishra Conceptualization, Methodology Writing- Original draft preparation, Anshul Gangele Supervision, Data curation, Visualization, Investigation, Writing- Reviewing, Veerendra Kumar Supervision, Conceptualization, Methodology, and Editing

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