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Optimizing Bio-Implant Materials for Femur Bone Replacement: A Multi-Criteria Analysis and Finite Element Study

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Abstract:- This study investigates and analyses alternative materials for replacing the femur bone in the human body, addressing the critical need for bio-implant materials arising from injuries, diseases, or natural deterioration. The femur, as the largest and strongest bone, is indispensable for mobility and weight support. Surgical intervention often necessitates the replacement of damaged femurs with suitable bio-implant materials.

Using the Analytic Hierarchy Process (AHP), this study selects optimal materials considering corrosion resistance, biocompatibility, Young's modulus, fatigue strength, and tensile strength—to replace the femur. A geometric model of the femur bone is constructed using a modelling package, enabling finite element analysis (FEA) to evaluate the endurance and suitability of selected bio-implant materials.

The FEA is conducted on two materials—stainless steel and titanium alloy—to assess their performance as femur replacements. Through comprehensive analysis, this research aims to contribute insights into the efficacy and viability of alternative bio-implant materials for femur bone replacement.

Keywords:- *Bio-Implant Materials, Analytic Hierarchy, Process, Finite Element Analysis*

I. INTRODUCTION

The femur bone, located in the upper leg, is along, strong bone that is essential for maintaining an individual's ability to walk and bear weight. When the femur is compromised due to fractures, degenerative conditions, or other factors, surgical intervention is required, often involving the use of artificial implants. Traditional implants are typically made of materials like metals, such as titanium and stainless steel, which have been used successfully in the past. However, these materials may have limitations, including stress shielding, potential for allergic reactions, and a lack of biological integration. Therefore, the aim of this project is to explore and assess alternative materials for femur bone replacement.

A. Need of Femur Bone

The femur, or thigh bone, is one of the longest and strongest bones in the human body, and it serves several crucial functions:

- Support and Structure: The femur provides structural support to the body, especially during weight-bearing activities like standing, walking, running, and jumping. It bears the weight of the body and helps maintain posture.
- Mobility: As a major bone of the leg, the femur plays a vital role in mobility. It articulates with the pelvis at the hip joint and with the tibia and patella at the knee joint, allowing for a wide range of motion.
- Muscle Attachment: Various muscles of the thigh, hip, and buttocks attach to the femur. These muscles are responsible for movement at the hip and knee joints. The femur provides a stable anchor point for these muscles to generate force and produce movement.
- Production of Blood Cells: The bone marrow within the femur is a site for the production of blood cells, including red blood cells, white blood cells, and platelets. This process, known as hematopoiesis, is vital for the body's immune function and oxygen transport.
- Storage of Minerals: The femur, like other bones, serves as a reservoir for minerals such as calcium and phosphorus. These minerals are essential for maintaining bone strength and integrity, as well as for various metabolic functions throughout the body.

Overall, the femur is indispensable for human movement, stability, and overall skeletal health. Injuries or diseases affecting the femur can significantly impair mobility and quality of life.

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B. Parts of Femur Bone:

The femur bone, or thigh bone, consists of several anatomical parts:

- Head: The proximal end of the femur forms a rounded structure called the head. It articulates with the acetabulum of the pelvis to form the hip joint. The head is covered with articular cartilage and connects to the femoral neck.
- Neck: The neck of the femur is a relatively narrow region that connects the head to the shaft (body) of the femur. It angles outward from the head, contributing to the characteristic shape of the femur.
- Greater Trochanter: This is a large, bony prominence located on the lateral (outer) aspect of the proximal femur. It serves as an attachment point for several muscles of the hip and thigh, including the gluteus medius and minimus.
- Lesser Trochanter: The lesser trochanter is a bony projection located on the medial (inner) aspect of the proximal femur, just below the femoral neck. It serves as an attachment site for the iliopsoas muscle.
- Shaft (Body): The shaft, or body, of the femur is the long, cylindrical portion between the proximal and distal ends. It is relatively thick and strong, providing structural support and bearing weight during activities such as walking and running.
- Medial and Lateral Condyles: At the distal end of the femur are the medial and lateral condyles. These are large, rounded bony protrusions that articulate with the tibia to form the knee joint. The condyles are covered with articular cartilage and are essential for smooth movement and weight distribution within the knee joint.
- Intercondylar Fossa: This is a groove located between the medial and lateral condyles on the posterior aspect of the distal femur. It provides space for structures like the cruciate ligaments and menisci of the knee joint.
- Epicondyles: Above each condyle are bony prominences known as epicondyles. These serve as attachment points for ligaments and tendons involved in stabilizing the knee joint and connecting muscles of the thigh.

II. LITERATURE REVIEW

The optimization of bio-implant materials for femur bone replacement is a multifaceted challenge that intersects material science, biological responses, corrosion resistance, and finite element analysis (FEA). This literature review synthesizes key findings from prominent sources to provide a comprehensive understanding of the interdisciplinary efforts in this field.

Dr. Mahmoud M. Farag’s book, "Material and Process Selection for Engineering Design,"[1] offers a foundational understanding of selecting appropriate materials for bio-implants, focusing on mechanical properties, biocompatibility, and manufacturability (Farag, 2009). Farag emphasizes a multi-criteria approach, integrating both qualitative and quantitative factors to ensure optimal performance and longevity of implants. This methodological framework balances structural integrity and biological compatibility, which is crucial for femur bone replacement.

James M. Anderson's article "Biological Responses to Materials,"[2] published in the Annual Review of Materials Research, explores the interactions between biomaterials and biological tissues. Anderson (2001) highlights the importance of understanding the body's immune response, inflammation, and tissue integration in designing bio-implants. Materials must elicit favorable biological responses to avoid complications such as rejection or infection, guiding the selection and modification of materials to enhance biocompatibility and successful integration with host tissue.

The study by Kamachi Mudali U. et al., "Corrosion of Bio-Implants," [3] published in Sadhana, examines the challenges posed by the corrosive environment within the human body. Mudali et al. (2003) discuss the susceptibility of various materials, including metals and alloys, to corrosion when used as bio-implants. The paper emphasizes corrosion resistance to extend the lifespan and maintain the mechanical integrity of implants. The authors advocate for coatings and surface treatments to mitigate corrosion, enhancing the durability and safety of bio-implants.

Niraj V. Gharat et al.'s review, "Finite Element Analysis for Design of Bio-Implants,"[4] published in Materials Today: Proceedings, examines the use of FEA to optimize bio-implant design. Gharat et al. (2020) demonstrate how FEA predicts mechanical behavior under physiological loads, identifying potential failure points to inform design improvements. This computational method refines structural design and material selection for femur bone replacements, enhancing implant performance and safety.

The article by T.S. Rajamohan et al., "Material Selection for Bio-Implants Using Analytical Hierarchy Process (AHP) and TOPSIS,"[5] also published in Materials Today: Proceedings, explores advanced decision-making techniques for selecting bio-implant materials. Rajamohan et al. (2020) integrate AHP and TOPSIS methods to evaluate and rank materials based on multiple criteria, including mechanical properties, biocompatibility, and corrosion resistance. This approach allows for comprehensive assessment and selection of suitable materials for specific applications, highlighting the utility of multi-criteria decision-making frameworks.

Thomas L. Saaty's seminal work on the Analytic Hierarchy Process (AHP) [6] provides a theoretical foundation for multi-criteria decision-making in material selection. Saaty’s AHP methodology structures complex decisions into a hierarchy of criteria, allowing systematic

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comparison of alternatives. This method incorporates both objective data and subjective judgments, making it applicable to bio-implants where diverse factors must be considered.

T Tandon's study, "Bio-Implant Stress Analysis of a Human Femur Bone Using ANSYS," [7] published in Materials Today: Proceedings (2015), explores using ANSYS software for stress analysis in bio-implants. Tandon (2015) demonstrates how finite element modeling assesses stress distribution within a femur bone implant under various loading conditions. Stress analysis predicts potential failure points, optimizing design to enhance implant performance.

Optimizing bio-implant materials for femur bone replacement requires an interdisciplinary approach involving material science, biological responses, corrosion resistance, and computational analysis. In the current study, AHP has been implemented by considering four alternatives for bio-implant materials. Considering the top best two materials finite element analysis has been performed and results were obtained.

III. ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP) is a decision-making technique that helps individuals or groups systematically analyze and prioritize multiple criteria when making complex decisions. Developed by Thomas L. Saaty, AHP involves breaking down a decision problem into a hierarchical structure of criteria and alternatives.

AHP applied to selection of bio-implant materials

- Define the problem: The problem is to select the most suitable bio-implant material among stainless steel, copper, composites, and titanium alloy for manufacturing an artificial femur bone. The criteria for evaluation include biocompatibility, corrosion resistance, toughness, fatigue strength, Young's modulus, and tensile strength.
- Develop a hierarchy: Organize the decision criteria and alternatives into a hierarchical structure. The main objective is selecting the best bio-implant material, with criteria listed below it and the four alternative materials listed as subcategories.
- Pair wise comparisons: Compare each criterion against every other criterion and assign relative importance scores using the Saaty scale. Repeat this process for the alternative materials, comparing each material against every other material for each criterion.
- Calculate weights: Use the pair wise comparison scores to calculate the relative weights of the criteria and the relative importance of each material for each criterion.
- Perform alternatives evaluation: Evaluate the performance of each alternative material against each criterion and assign scores accordingly. This could involve qualitative or quantitative assessments based on available data or expert judgment.
- Aggregate scores: Multiply the scores for each alternative material by the corresponding weights of the criteria and sum them to obtain an overall score for each material. This represents the suitability of each material relative to the decision criteria.
- Select the best material: Identify the material with the highest overall score as the most suitable bio-implant material for manufacturing the artificial femur bone.

Figure- 1 indicates the AHP tree for selection of bio-implant materials and table-1 portrays the properties considered for comparing different alternate materials. And table-2 shows the priorities of the alternate bio-implant materials after implementing AHP technique.

IV. RESULTS AND DISCUSSION

The model of the femur bone considered for finite element analysis is shown in the fig.2. Only two materials, stainless steel and titanium alloy are considered for analysis. Considering an average person’s weight of 70 kg, finite element analysis has been performed on the femur bone. Following observations were made.

- Stainless steel is endowed with high elastic modulus (200 GPa) and is very stiff. As a result, it has undergone a strain of 0.0000875. Titanium alloy’s elastic modulus is 124 GPa. As a result, it has undergone a strain of 0.0001591, which is higher than stainless steel.
- Stainless Steel: Higher stiffness (elastic modulus) leads to less deformation under the same load, which can be beneficial for maintaining structural integrity but may cause stress shielding.
- Titanium Alloy: Lower stiffness results in slightly more deformation, which is closer to the natural bone's behavior, promoting better load sharing and potentially reducing stress shielding effects.

In conclusion, titanium alloys (like Ti-6Al-4V) are often preferred for femur implants due to their more bone-like deformation characteristics and higher biocompatibility, despite stainless steel being stronger and stiffer. This balance helps in maintaining bone health and ensuring the longevity of the implant

V. CONCLUSIONS

The field of bio-implant materials for femur bone replacement is of paramount importance, given the prevalence of injuries, accidents, and natural deterioration affecting the human body. This project aimed to contribute to the advancement of this field by exploring alternative materials and evaluating their suitability using finite element analysis (FEA).

The study commenced by recognizing the critical need for bio-implant materials and identifying stainless steel, copper, and titanium alloy as potential alternatives for femur bone replacement. Utilizing the Analytic Hierarchy Process (AHP), these materials were prioritized based on key properties including corrosion resistance, biocompatibility, Young's modulus, fatigue strength, and tensile strength. Following material selection, a geometric model of the femur bone was constructed using advanced modeling techniques. This model served as the basis for conducting finite element analysis to assess the endurance and performance of the selected bio-implant materials.

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The analysis focused on two materials: stainless steel and titanium alloy. Through the examination of equivalent elastic strain, Von Mises stresses, and total deformation, valuable insights were gained into the behavior of these materials when used as femur bone replacements. In conclusion, the findings suggest that titanium alloy exhibits promising and reliable behavior as a bio-implant material for femur bone replacement. Its performance, as evidenced by the FEA results, highlights its potential to enhance the outcomes of femur bone replacement surgeries. However, further research and clinical validation are warranted to confirm these findings and optimize the utilization of bio-implant materials in orthopedic applications.

This study represents a significant step towards advancing the understanding and application of bio-implant materials in orthopedic surgery, ultimately aiming to improve patient outcomes and quality of life.

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Table-1: Criterion Considered for Selection of Alternatives

S. No	**Material**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	Stainless Steel	10	7	200	517	8	0.3
2	Copper Alloy	10	9	238	655	2	0.34
3	Titanium Alloy	8	10	124	985	7	0.34
4	Composites	7	7	22	680	3	0.3

P1-Biocompatibility
P2- Corrosion resistance
P3-Young’s Modulus (GPa)
P4-Tensile Strength (MPa)
P5-Toughness
P6-Poisson’s Ratio

Table-2: *Priorities of Alternate Material*

S. No	**Material**	**Weights**	**Priorities**
1	Copper Alloy	0.242	3
2	Stainless Steel	0.285	2
3	Titanium Alloy	0.442	1
4	Composites	0.064	4

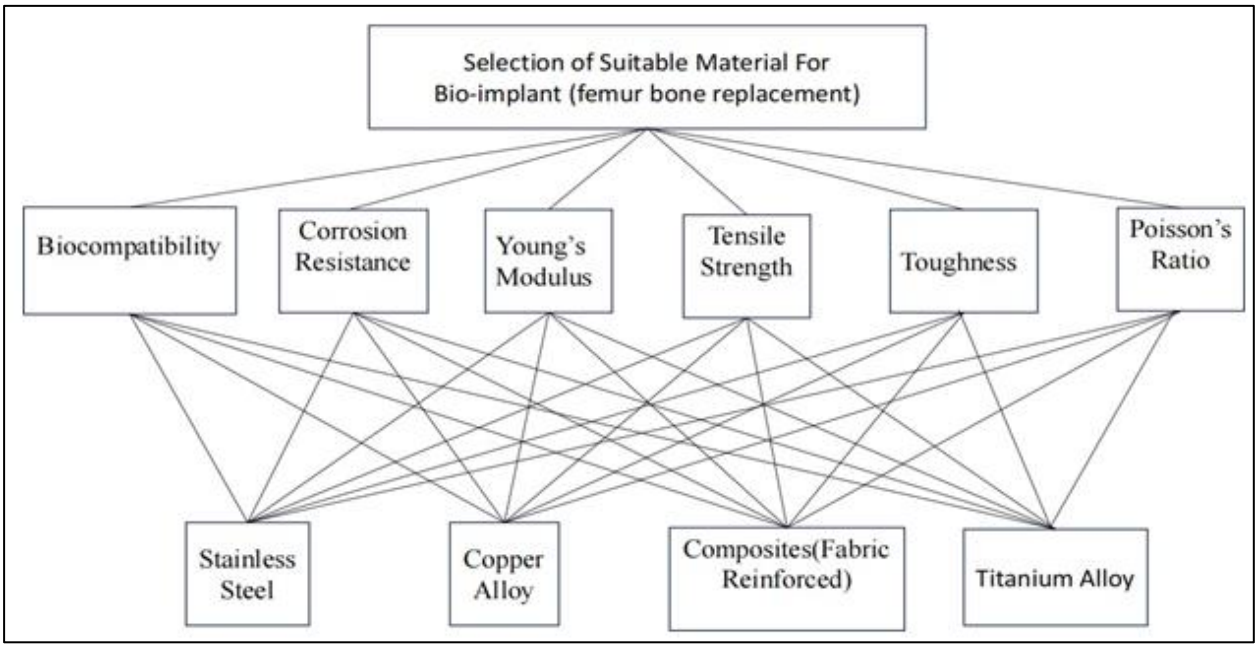

Fig.1 AHP Tree for Selection of Bio-Implant Materials

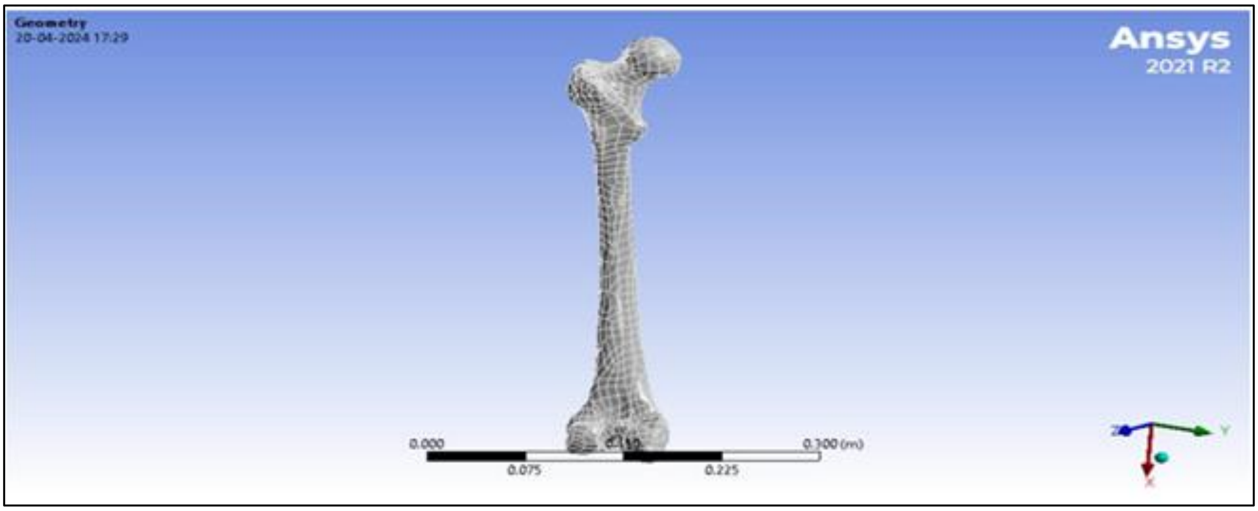

Fig. 2 Meshed Model of Femur Bone