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Structural and Biomechanical Analysis of the Artificial Hintegra Ankle Prosthesis

Structural Integrity and Biomechanical Performance Evaluation

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***Abstract*— When treating severe arthritis in the ankle joint, Total Ankle Arthroplasty (TAA) is a good substitute for arthrodesis. Ankle joints that have been removed or injured can also be replaced with it. In order to determine whether the Hintegra artificial ankle prosthesis can effectively replace damaged human ankle joints, this research will develop and evaluate the device. Making a prosthesis that fits people of all sizes, performs well, and has a greater success rate with fewer failures is the aim.**

The first step in the project is creating a computer-aided design (CAD) model of a prosthetic ankle that functions and appears like a natural joint. The model will be examined using Finite Element Analysis (FEA) to determine how it functions under various forces and circumstances.

To make the prosthesis appropriate for a broad spectrum of patients, the design will consider variations in people's height, weight, and degree of activity. The goal of this research is to develop a robust and dependable ankle replacement that will allow patients with injured ankle joints to move normally again.

Keywords—Total Ankle Arthroplasty (TAA), Hintegra Ankle Prosthesis, Finite Element Analysis (FEA), Computer-Aided Design (CAD), Biomechanical Performance, Structural Integrity, Ankle Joint Replacement

I. INTRODUCTION

The human ankle joint is critical for walking, running, and balance because it allows for movements like dorsiflexion and plantarflexion, which are necessary for weight-bearing, mobility, and stability.[8] But it is vulnerable to problems like degenerative diseases, overuse, and trauma. Among these, arthritis is a prevalent and crippling ailment that causes pain, stiffness, and decreased movement, especially osteoarthritis and post-traumatic arthritis.[2] Severe arthritis can cause instability and joint deformity, which greatly hinders day-to-day activity.[3] Ankle arthritis affects about 1% of Americans and is becoming more common as a result of aging, obesity, and trauma, posing a significant financial and personal hardship.[2] Surgical procedures such as total ankle arthroplasty (TAA) or arthrodesis (joint fusion) are frequently required for more severe patients. While arthrodesis improves pain, it compromises mobility and increases stress on neighboring joints.[2] By using an artificial joint to restore function and movement, TAA offers a more hopeful approach. The capacity of the Hintegra ankle prosthesis, a cutting-edge TAA design, to closely resemble natural ankle biomechanics makes it unique. Better range of motion, less strain on nearby tissues, and flexibility to meet changing patient needs are all made possible by its superior anatomical design, modularity, and longevity.[2] The increasing prevalence of ankle arthritis emphasizes the necessity for effective and flexible remedies. For impacted patients, prosthetics such as the Hintegra provide better results by improving mobility, function, and general quality of life.[2]

II. ANATOMY OF ANKLE JOINT

A. The ankle joint is a hinge joint that joins the foot and lower leg. The tibia, fibula, and talus bones make up the joint. [4]. Fig:1 [4]

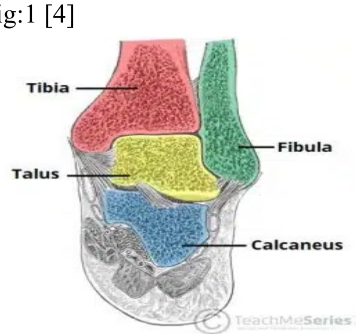

Fig.1. The bones of the ankle joint; tibia, fibula and talus.

Note that the calcaneus is not considered part of the ankle joint.

Articulating Surface:

The Hintegra imitates the talar dome and mortise, which are the tibia and fibula's natural bracket-shaped sockets.

In order to reduce friction during movement, components are made to mimic the function of cartilage.

Stability of Ligaments:

To avoid instability, the prosthesis maintains the normal tension of the lateral and doltoid ligaments.

Anatomical variances are accommodated by modular sizing, which guarantees balanced ligament support.

Biomechanical Motions:

uses a hinge-like construction to facilitate dorsiflexion, plantarflexion, inversion, and eversion, simulating actions driven by muscles (e.g., gastrocnemius, tibialis anterior).

Clinical Modifications:

restores alignment and weight distribution to treat post-traumatic disorders (such Pott's fractures).

Anatomical fit is ensured by customized size using patient-specific X-rays, which is essential for joint longevity and less stress on nearby tissue.

III. CAD Model And Dimension

Each patient has distinct ankle measurements and medical issues, necessitating a customized strategy. The first step in the process for the Hintegra prosthesis is to take an ankle X-ray of the patient. After that, the X-ray is examined to obtain the measurements needed to create a new device that fits precisely. In contrast to conventional "one size fits all" implants, the Hintegra prosthesis focuses on attaining proper ligament tension and comes in a range of sizes. Detailed dimensions obtained from X-ray analysis served as the foundation for the model developed in this work. Fig:4 [5]

Fig.4. Hintegra Artificial Ankle showing different components

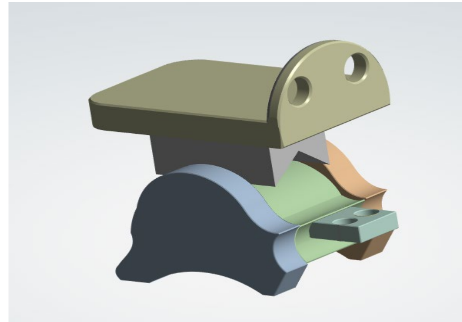

Fig.5. CAD Model

IV. Mathematical Calculations

When an individual is moving, such as when walking, jogging, or standing, torque is produced in the ankle joint. The ankle joint's rotation center is not the same as the stress point, which is where the force acts. Running and other similar sports put a lot of strain on the forefoot, which causes a lot of torque around the joint. A lever arm is created by the misalignment between the rotating center and the stress point, and this arm is crucial for generating the torque required for movement. This knowledge is essential to guarantee that the ankle replacement can successfully tolerate and adjust to dynamic pressures.

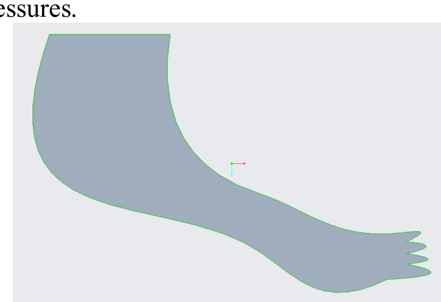

Fig.6. Foot Alignment During Walking

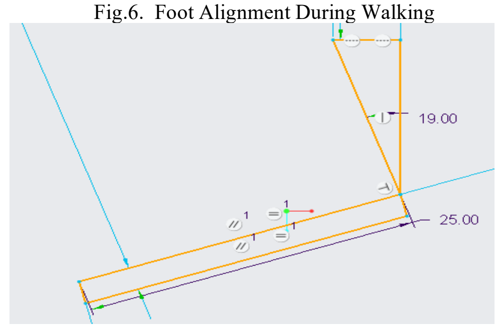

Fig.7. Free Body Diagram

Here, F N=1423N, F B=-1423N, θ = 19°

$\tau = FN \cdot \Upsilon$

$F\,N = -FB\cos\theta\Upsilon$

Thus,

$\tau = -FB\cos\theta\Upsilon$

$= -1423N\ (\cos 19°)(\ 25cm\ )(1/100) = -336.369\ Nm$

When people walking feel -336.369Nm clockwise torque.

V. FINITE ELEMENT ANALYSIS

To assess the Hintegra prosthesis's structural and biomechanical performance under varied loading scenarios, Finite Element Analysis (FEA) was performed on it. The analysis evaluated the prosthesis' stability, longevity, and capacity to replicate the behavior of the ankle joint by simulating real-world pressures and stresses. Important insights for improving the design to guarantee dependability and patient safety were obtained from this procedure

Material Selection: Table1 [9,10,11,13]

	Component	Material	Density(kg/m3)	Thermal Expansion Coefficient(1/C)	Young's Modulus(GPa)	Poission's Ratio	Yield strength(MPa)	FOS
1	Tibial Component	Titanium Alloy(Ti-6Al-4v)	4620	9.4E-06	110	0.36	950	5.1
2	Talar Component	Cobalt Chromium Alloy	8300	1.4E-05	210	0.3	900	5.6
3	Polyethylene Insert	CFR-PEEK (Carbon Fiber Reinforced PEEK)	1.5g/cm3	15E-06	22	0.30	250	5

TABLE.1. MATERIAL SELECTION

A. Applying Boundary Condition

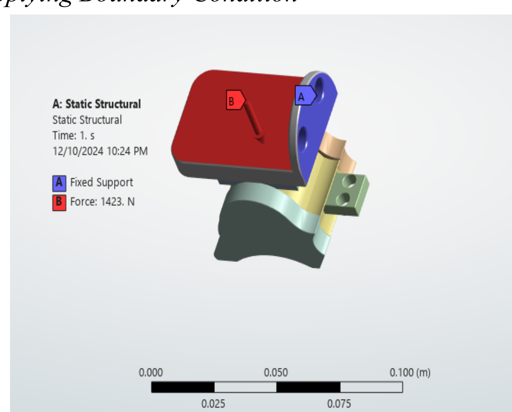

Fig.8. Boundary Conditions

On the upper surface of the tibial component, an 1423 N stress is applied using the formula F= 160 lb /2*4 , which is equivalent to the body weight of a 160-pound person. In order to restrict movement and mimic the talar component's attachment to the bone, fixed support is given to its side surface. By directing the weight vertically downward along the negative Y-axis, actual compressive forces are replicated.[13] The goal of these boundary conditions is to replicate the artificial ankle joint's mechanical behavior in my project.

B. Mesh

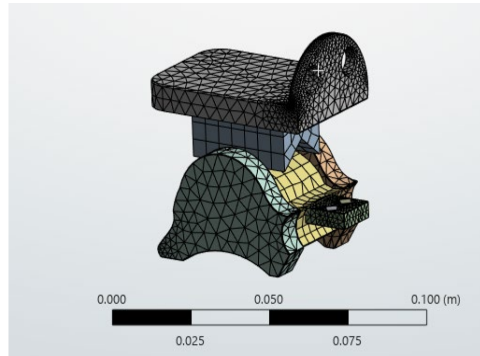

Fig.9. Mesh

In order to accurately calculate stress, strain, and deformation under applied loads and boundary conditions, the geometry is divided into smaller pieces by the process of meshing. It guarantees that important information in load-bearing and high-stress areas are captured in the simulation.

C. Total Deformation

Overall displacement is measured using total deformation, which also guarantees that the prosthesis is stable when loads are applied. [12]

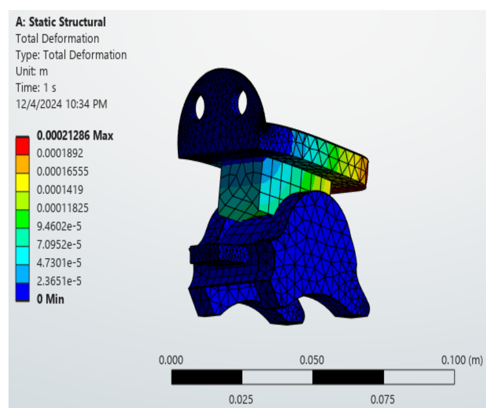

Fig.10. Total deformation of Hintegra Artificial Ankle

Here 1423N load was applied at the top of the tibial component. In figure it is indicated that the total deformation of this device with minimum deformation is 0 and maximum deformation is 0.00021286 or 2.1286e-04.

Total Deformation	Results(m)
Max	2.1286e-04
Min	0

TABLE.2. Total Deformation Results

D. *Equivalent (Von Mises) stress result*

In order to ensure that the design is safe under applied loads, equivalent Von Mises stress is used to anticipate material failure by integrating stresses into a single value for comparison with yield strength [13]

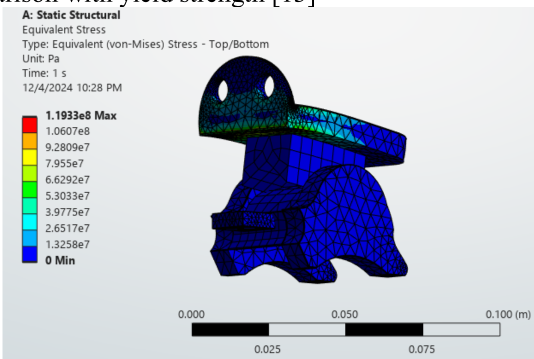

Fig.11. Equivalent (Von-mises) stress

It is safe to use in artificial human ankle joints since, when 1423N of force is applied, the maximum equivalent von Mises stress 1.1933e8 Pa or 119.33Mpa is less than the yield strength of cobalt-chromium alloy (900 MPa) and titanium alloy (830 MPa). This guarantees the materials won't go over their elastic limits when loads are applied.

Equivalent (Von-mises) stress	Results(Pa)
Max	1.1933e+08
Min	0

TABLE.3. Equivalent Von-mises stress results

E. *Equivalent Elastic Stress result*

The amount that a material stretches or deforms under load is measured by its equivalent elastic strain. It guarantees the design is strong and long-lasting and helps verify that the material stays within safe bounds to prevent permanent damage.

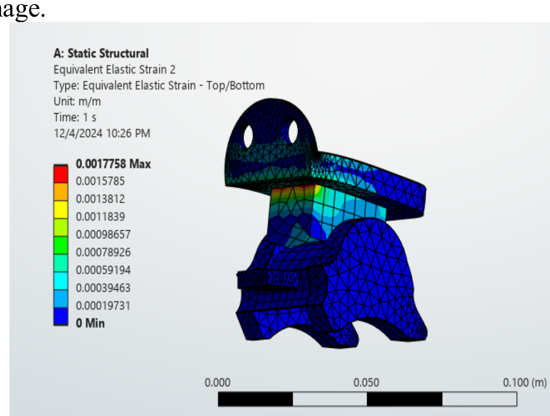

Fig.12. Equivalent Elastic Strain

From the diagram the max elastic strain is approximately 1.7758e-3 which does not exceed the elastic limit of the materials used here. So, this Hintegra Artificial Ankle gives high success rate.

Equivalent Elastic Strain	Results
Max	1.7758e-3
Min	0

TABLE.4. Equivalent Elastic Strain Results

F. *Factor of Safety*

The ratio of the material's strength to the maximum stress in the component is known as the safety factor.

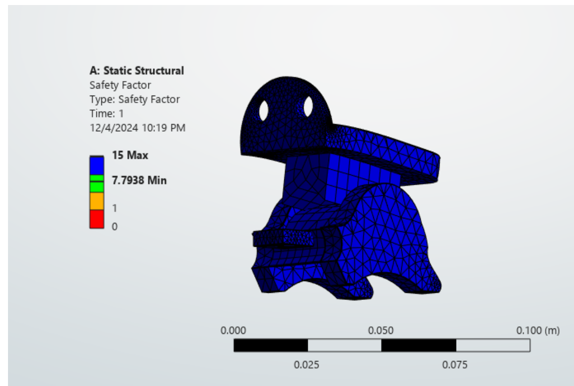

Fig.13. Factor of Safety (FOS)

For this model maximum safety factor is 7.7938. That means it can hold up to (7.7938*1423)=11090N. Therefore the model is the perfect replacement for the patient for walking, running and standing. It is safe.

FOS	Results
Max	15
Min	7.7938

TABLE.5. FOS results

VI. Conclusion

With a high success rate and low failure rate, the artificial Hintegra ankle replacement device was made to be affordable, dependable, and long-lasting. Creo was used to construct the CAD model, and Ansys was used for simulation analysis. According to the results of the FE Analysis, the model may function exceptionally well, giving patients greater mobility and the confidence to walk, run, and move. This strategy demonstrates the possibility of cutting-edge prosthetic devices catered to individual patient requirements.

Acknowledgment

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