ANALYSIS OF ANKLE JOINT WITH ARTICULAR CARTILAGE

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Abstract: Developing an accurate finite element model of an ankle joint is a challenging task and time consuming. The objective of this paper is to model, simulate and analyze the effects of loading on the viscoelastic behavior of human articular cartilage at the ankle joint. Dataset of a healthy male volunteer is to taken to reconstruct a detailed three-dimensional model of an ankle joint. The bone models are segmented into two types of bones - cortical and cancellous according to the Hounsfield unit. The ankle model consists of tibia, fibula, talus, calcaneus, cuboid, navicular bones cartilage. The cartilages were constructed using prony series viscoelastic properties. . The ankle joint is modeled in CATIA V5 and Analysis is performed in ANSYS 16.1 Workbench. Two kind of Analysis, Static and Transient Analysis were conducted on the cartilage and its replacement materials like Poly Vinyl Alcohol (PVA) and Polyethylene glycol (PEG) and Von-Mises Stresses and deformations along Z axis are tabulated for different forces. From the simulation results one can conclude that PVA and PEG can replace the cartilage for the said conditions.

Index Terms - Neural networks, face recognition, fuzzy system, Neuro-fuzzy.

I. INTRODUCTION

Articular cartilage is a thin layer of specialized connective tissue with unique viscoelastic properties. It is a translucent, heterogeneous load processing gel that overlays the end of the articulating bones of mammalian joints. Its principal function is to provide a smooth, lubricated surface for low friction articulation and to facilitate the transmission of loads to the underlying sub-chondral bone. It is a complex tissue, which covers the ends of long bones in synovial joints. It protects the subjacent bone from high friction, increases contact area, and consequently improves the local joint congruence. Articular cartilage is a biphasic material that consists of a solid and a fluid phase.The mechanical properties of articular cartilage in load bearing joints such as knee and hip have been studied extensively at macro, micro and nano-scales. The mechanical functions alone would probably not be sufficient to justify an in-depth study of cartilage biomechanics. The mechanical properties include the response of cartilage in frictional, compressive, shear and tensile loading. Cartilage is resilient and displays viscoelastic properties. Lubricant, a glycoprotein abundant in cartilage and synovial fluid, plays a major role in bio-lubrication and wear protection of cartilage. Cartilage damage is difficult to heal. Also, because hyaline cartilage does not have a blood supply, the deposition of new matrix is slow.

II. LITERATURE REVIEW

Over the few years, surgeons and scientists have elaborated a series of cartilage repair procedures that help to postpone the need for joint replacement. Several diseases can affect cartilage. Some common diseases affecting are osteoarthritis, spinal disc herniation, traumatic rupture, achondroplasia, costochondritis, and relapsing polychondritis. The most common of all these is Osteoarthritis, which occurs due to the result of either traumatic mechanical destruction, or progressive mechanical degeneration i.e wear and tear. Dr. SadiqJaferAbbass et.al [2] in their paper conclude that current clinical methods for the diagnosis of osteoarthritis include X-ray, magnetic resonance imaging, and arthroscopy. These methods may be insensitive to the earliest signs of osteoarthritis. Mechanical degeneration occurs with progressive loss of normal cartilage structure and function. This initial loss begins with cartilage softening then progresses to fragmentation. As the loss of articular cartilage lining continues, the underlying bone has no protection from normal wear and tear of daily living and begins to break down. Andrew D. Pearle, et.al [1] in their paper concluded that in end-stage disease, clinical characteristics including various degrees of joint pain, stiffness, dysfunction, and deformity are easily recognized. However, signs and symptoms in earlier stages, when treatment may alter disease course, are more elusive. Understanding the basic science of cartilage and the changes that occur in OA is imperative to develop novel strategies to diagnose and treat this disorderKazemi M. et.al [5] in their paper concluded that due to load bearing role of the meniscus, injuries are very common in this tissue and maximal stress in articular cartilage in meniscectomy joint was reported about double of that in an intact joint.

The treatment of articular cartilage injuries is made in two ways: operative and non-operative treatments. Non-operative treatments include oral medications, physical therapy, weight loss, bracing and injections. Such management is often ineffective in highly active and symptomatic patients and may prove beneficial in low-demand patients. In operative treatments the various methods are anthroscopic debridement and lavage, repair simulation techniques, cell and tissue transplants. Though there are many treatments available for this ailment cartilage replacement is one of the best emerging options. This replacement can be done with materials called as Hydrogels.

Polyvinyl alcohol (PVA) is a synthetic polymer derived from polyvinyl acetate through partial or full hydroxylation,Polyvinyl alcohol is an odourless, tasteless and translucent, white or cream coloured substance. Maribel I. Baker. et.al [5] in their paper concluded that PVA is commonly used in medical devices due to its low protein adsorption characteristics, biocompatibility, high water solubility, and chemical resistance. Kaifeng Liu [3] in his work demonstrated that PVA hydrogels manufactured with high polymer concentration can improve mechanical properties. Polyethylene glycol (PEG) is a macromolecular polymer gel constructed of a network of cross-linked polymer chains.PEG hydrogels are fluid-filled crosslinked three-dimensional networks, consisting of covalently bonded PEG chains,. Its biocompatibility and flexible properties make it ideal for use in various applications. Many advantages exist in hydrogels such as high water content, large deformability. Quynhhoa T. Nguyen et.al [6] in their paper concluded that PEG hydrogels could mimic a broad range of the compressive and tensile mechanical properties of articular cartilage.References [7,8] purpose is to review the literature that discusses normal anatomy and biomechanics of the foot and ankle, mechanisms that may result in a lateral ankle sprain or syndesmotic sprain, and assessment and diagnostic procedures.

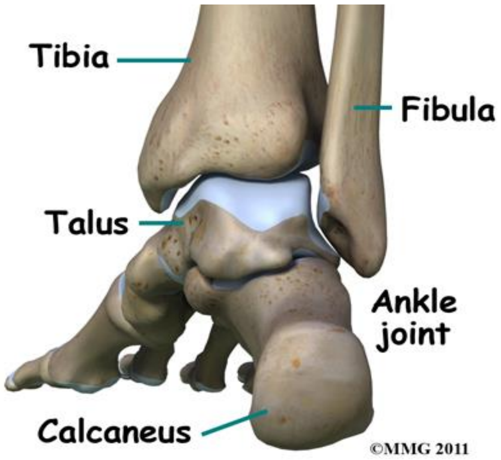


Figure 1: Ankle joint with cartilage

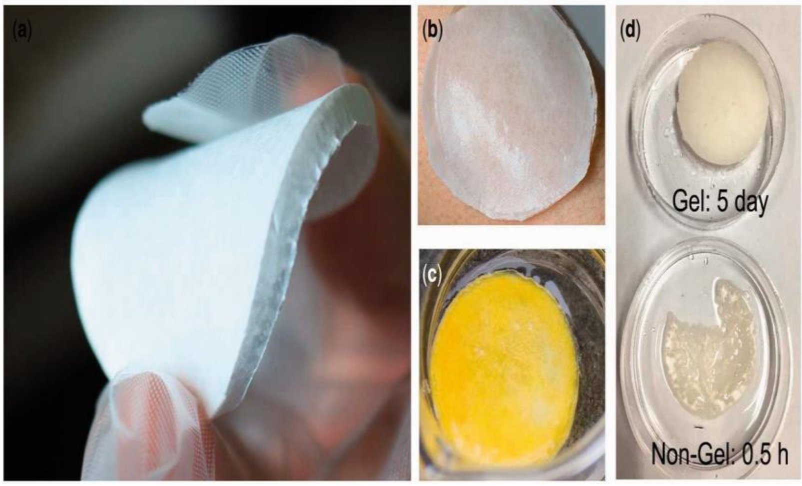


Figure 2: Preparation of hydrogel

Therefore, in this paper, mechanical behavior of human articular cartilage under various load is studied and an attempt is made to suggest replacementmaterials for cartilage. Polyvinyl alcohol (PVA) and Poly ethylene glycol (PEG) are the two synthetic polymers considered in this paper.

III. PROBLEM DISCRIPTION

The objective is to model an ankle joint with cartilage using available FEM software and then replace the cartilage with bio-compatible materials like Polyvinyl alcohol (PVA) and Polyethylene glycol (PEG) and compare their performances under various loading conditions and arrive at best replacement for cartilage material. The articular cartilage due to different mechanical activities can get worn out. Since it does not have any blood supply it cannot repair itself. Once the damage is initiated, cartilage degeneration happens very fast and it is irreversible.

Loading conditions are 400N, 600N and 900N applied the top surface of tibia, output is measured in terms of total deformation and von Mises stresses. The load of 400 N, 600N and 900 N corresponds to persons of average weight 80 kgs (Normal) 120 kg(over weight) and 180 kg (extreme) respectively.

Table 1:Material properties of cartilage,PVA and PEG.

Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)	Yield Strength (MPa)
Articular Cartilage	0.450	0.106	1100	4
PVA	0.430	`0.22	1190	3
PEG	0.520	0.3	1128	2.5
Bone	18*10^3	0.3	1750	-

Table 2:Prony series for cartilage,PVA and PEG.

Material	Shear relaxation modulus	Relaxation time
Cartilage	0.399	3.5
PVA	0.401	3.5
PEG	0.451	3.5

IV. METHODOLOGY

The methodology adopted for this purpose is as follows:

Determination of the dimensions of the ankle joint consisting of Tibia, Fibula and talus, calcaneous (hell bone) and articular cartilage are taken from journals [1].Using Catia V5 software, 2D sketches of Tibia, Fibula, calceneous, talus, cartilage are drawn (Figures 3 & 4) taking the dimensions from the journals [1,3]. Later 3D models were developed and assembled to form ankle joint, the cartilage between the joint is of 3 mm. The 3D model of ankle joint is then imported to Ansys 14.5 workbench.As the modeling of biphasic is found to be very difficult using FEM software, alternative method of assigning viscoelastic properties based on Prony series is choosen. The prony series properties(Tables 1 & 2) for AC, PVA, PEG and Bone were assigned using PYTHON coding(Figure 5). The element size is taken as 5 mm and the type of element (Figure 6) is brick element (comes by default). In case 1, load of 400 N is assumed to be applied on the top surface of the tibia & fibula for static analysis. Results in terms of Von Mises stresses and deformation in Z direction are tabulated as load is varied from 400, 600 & 900N respectively. Apply the same forces/load on the tibia and fibula to obtain the effect of replacement materials. In case 2, the load is varied from 400 to 700 in 5 seconds and applied on all the three materials, results are tabulated.

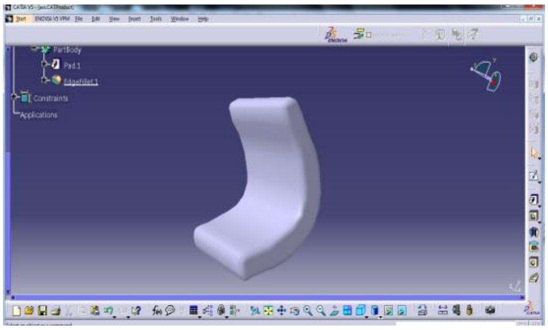


Figure 3: 3D model of the cartilage

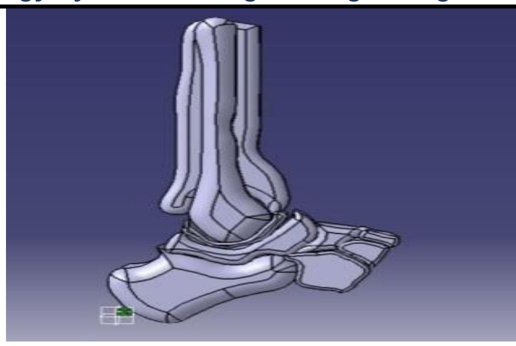


Figure 4: Model of Cartilage with tibia, fibula

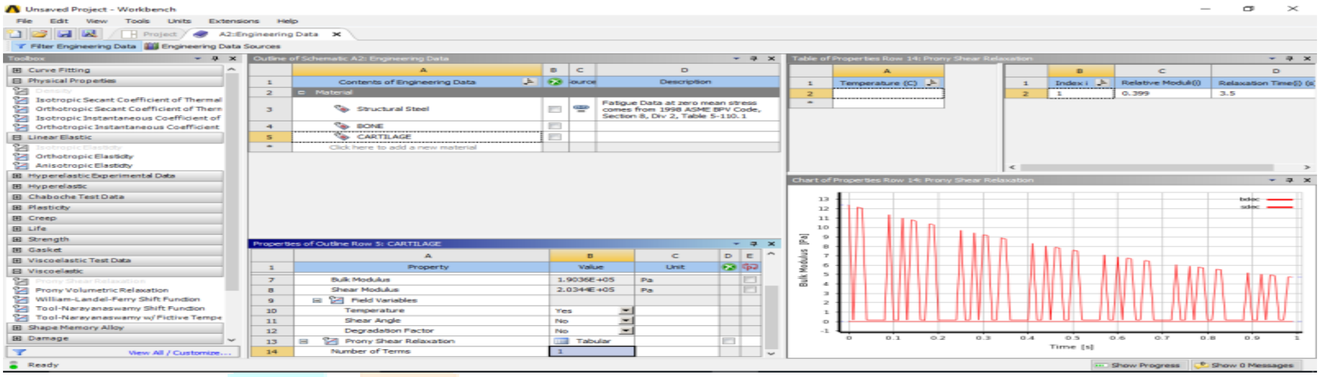


Figure 5: Properties of Cartilage.

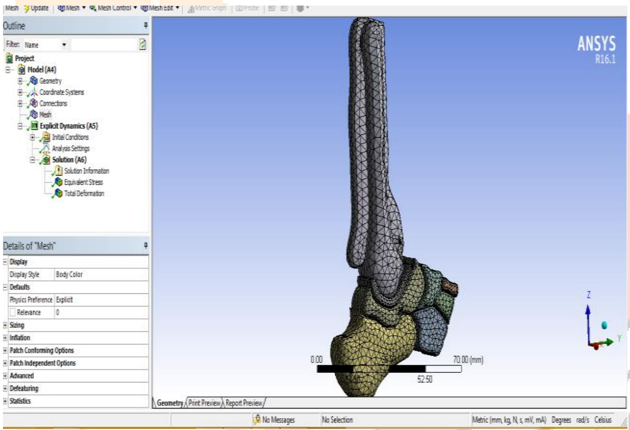
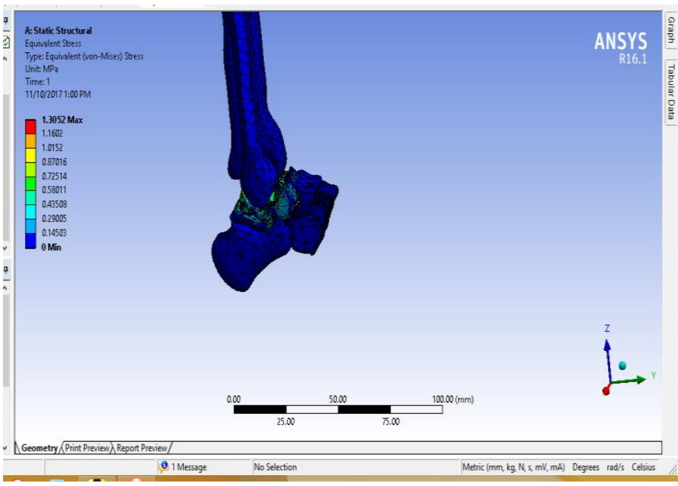


Figure 6 : Meshed model of cartilage with bone.

V. RESULTS AND DISCUSSIONS

From the analysis carried out on the 3D model of the cartilage, PVA & PEG, deformation and stress results have been obtained. The results are as follows



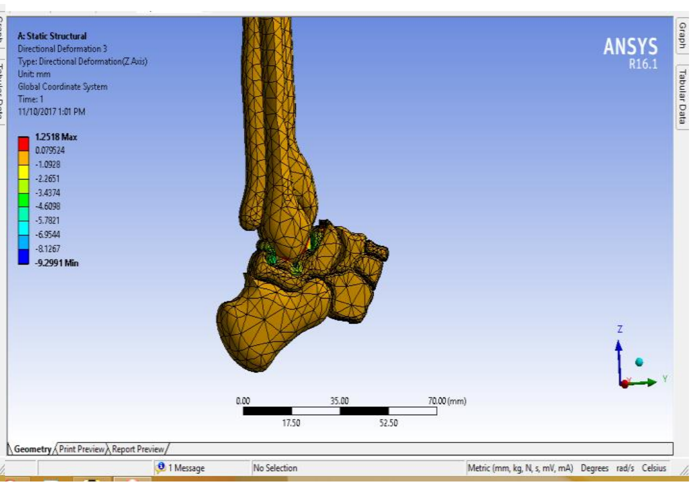


Figure 7:Von-mises stress on cartilage due to 400N force.

Figure 8:Directional deformation in Zfor cartilage due to 400 N

Case 1: Static Analysis

Table3 :Von-Mises Stress Developed In Cartilage, PEG and PVA due to Static Structural Analysis

Force (N)	Equivalent stress (MPa)		
	CARTILAGE	PEG	PVA
400	1.3052	1.3093	1.2321
600	1.9579	1.964	1.8481
900	2.9368	2.8478	2.6798

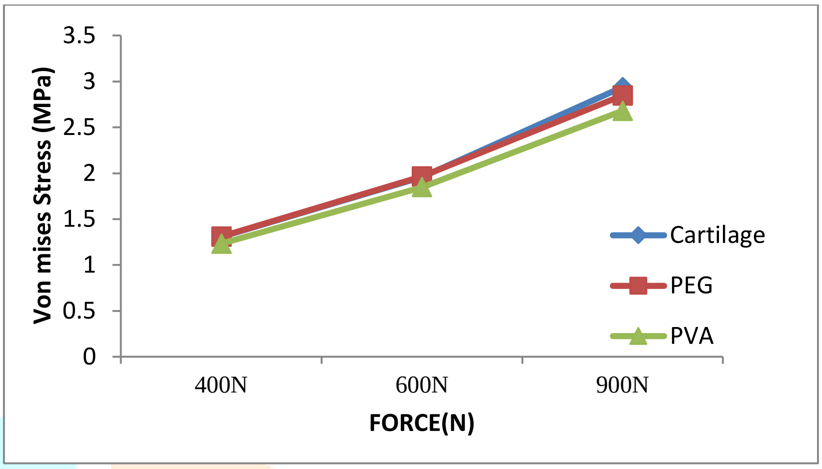


Figure 9: Von Mises stress variation under the application of load for all the three materials

Table 4: Directional Deformation along Z-Direction in Cartilage, PEG and PVA due to Static Structural Analysis

Force (N)	Directional Deformation (mm) in Z direction		
	CARTILAGE	PEG	PVA
400	1.2518	1.1222	1.3436
600	1.8778	1.6833	2.0154
900	2.8167	2.4408	2.9224

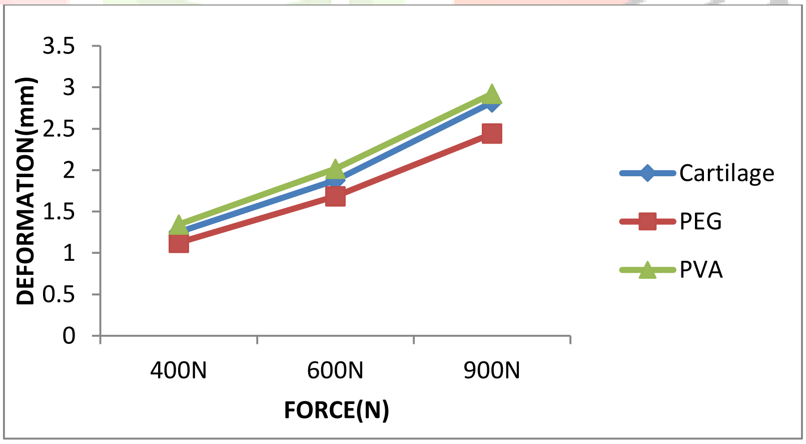


Figure 10: Directional Deformation of Cartilage in Z-direction due to Static Structural Analysis

Based on the results obtained, as seen from the Figures 9 and 10 and Tables 3 and 4, following observations can be made.As the load is increased, von Mises stresses and deformation in Z direction increased in all the three materials. Moreover von Mises stresses magnitude induced in PVA & PEG is less than AC. In case of deformation in Z direction, deformation in PVA is large followed by AC and PEG. Behaviour of joint made with PEG is not satisfactory at 900 N as stress induced is more than the yield strength of PEG(2.5 MPa). While in deformation the response of PVA material for 900 N load is not good as the deformation is about 2.9224 mm almost equal the thickness of material (3 mm).

Case 2: Transient Analysis

Transient Analysis is performed on Articulate Cartilage having 5 Step-controls for 5 seconds with varying load i.e., from 400N to 700N.

Table 5: Von Mises stress in AC, PVA &PEG (Transient)

Steps	Time(s)	FORCE (N)	Von-Mises Stress(MPa)		
			Cartilage	PEG	PVA

1	0	0	0	1	0
1	1	400	1.6564	1	1
2	2	450	1.8994	2	2
3	3	500	2.0722	3	3
4	4	600	2.4508	4	4
5	5	700	2.8324	5	5

Table 6: Deformation in Z direction for RAC,PVA, PEG

Steps	Time(s)	FORCE (N)	Directional Deformation in Z Direction (mm)		
			Cartilage		
1	0	0	0	1	0
1	1	400	1.7258	1	1
2	2	450	2.0289	2	2
3	3	500	1.6613	3	3
4	4	600	1.7147	4	4
5	5	700	1.9139	5	5

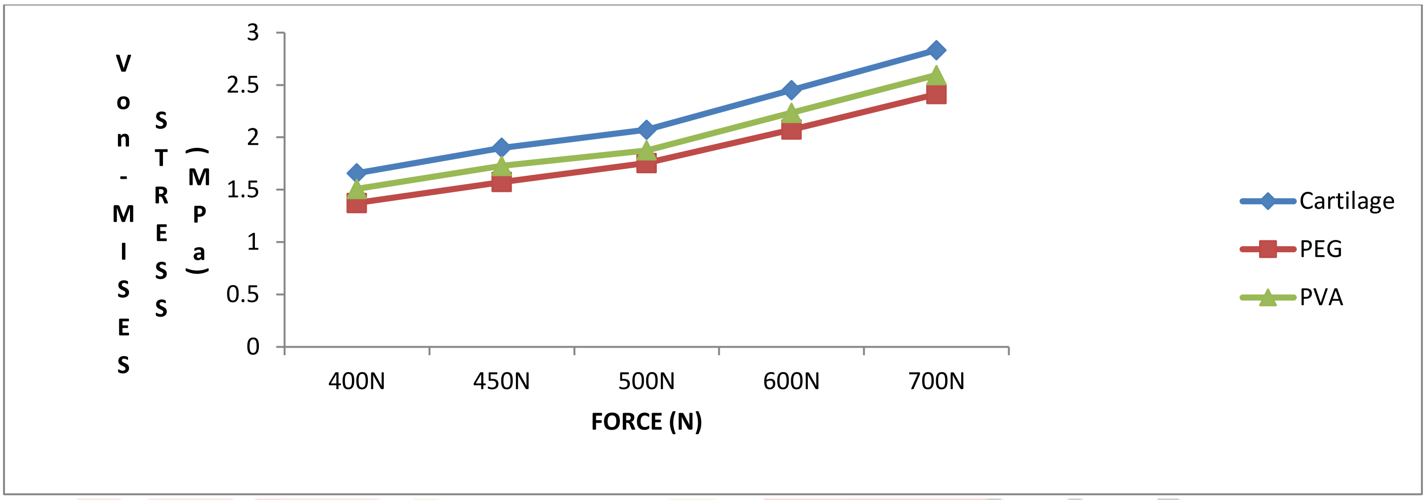


Figure 11: Von Mises stress variation under the application of transient load for all the three materials

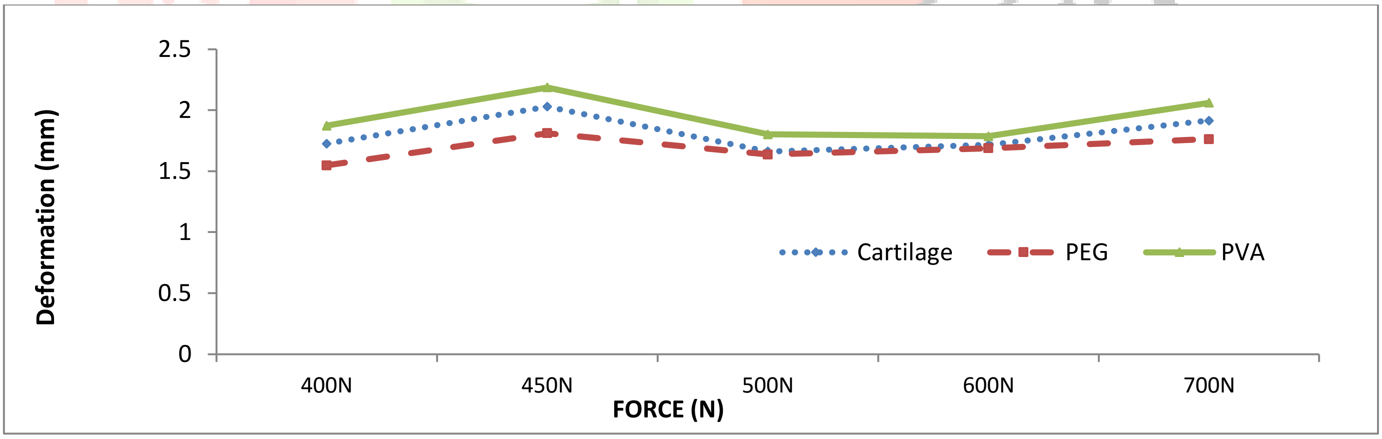


Figure 12 :Directional Deformation along Z-Direction in Cartilage, PEG and PVA due to Transient Analysis

The results obtained are given in 5 & 6 and figures 11 & 12. It can be deduced that the transient results are similar to the static results but the limiting values are obtained at 700 N against 900 N for static loading. PEG is failing first when compared with the other two materials at higher loads.

VI. CONCLUSIONS

The present study focused on the analysis of ankle joint with articular cartilage (AC). The effects of loading on the viscoelastic behavior of human articular cartilage at the ankle joint were analysed. Two kinds of analysis, Static and Transient Analysis were conducted on the cartilage and its replacement materials like Poly Vinyl Alcohol (PVA) and Polyethylene glycol (PEG) and Von-Mises Stresses and deformations along Z axis were determined. Following are the conclusions drawn from the above analysis:

- The von Mises stresses induced in AC material is 1.9579 N/mm^2, when a 600 N load is applied, Its yield strength is 4 MPa. Which yields a Factor of safety of 2. Similarly Factor of safety at this load for PVA and PEG is found to be 1.62 and 1.272. When loading is increased to 900 N both AR and PVA are safe but PEG is yielding.

- The von-Mises stresses in PVA are approximately 10% less than Articulate Cartilage as the load is increased from 400 N to 900 N.
- The obtained von-Mises stress for PVA at 900 N is 15% less than the Yield Strength of the material
- The obtained deformation results in PEG are 17 % less than PVA and 14 % less than AC under static analysis.
- Under transient loading, Factor of Safety of PEG is less than PVA which is less than AC. Deformation of PEG is 7 % less than AR and 14 % less than PVA.
- Based on the results obtained, PVA is better replacement material than PEG because stress induced on PVA is less than that of PEG. Moreover PEG is yielding at very high loads.

VII. REFERENCES

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