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Modeling And Biomechanical Analysis Of Human Knee Joint

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***Abstract*—The main objective of the present work is to implement the computer aided technology to study the biomechanical behavior of human knee joint which consists of Femur, Tibia, Patella, Menisci, Posterior Cruciate Ligament (PCL), Anterior Cruciate Ligament (ACL), Medial Collateral Ligament (MCL), and Lateral Collateral Ligament (LCL).**

Three-Dimensional (3D) model of knee joint was created. The Mechanical properties like young's modules, Poisson's ratio of the human bones will vary from person to person, in general according to age, weight, gender, and feeding habits. We considered for this work to create a 3D model using cadaver bones of male 30years old, 1.70m tall, and weight was 66kg.which is collected from Anatomy Department of SRM Medical College and Research Institute, Kattankulathur. The individual bones femur, tibia and patella are modeled using Solid Works. The biomechanical behavior of individual bone, assembly model and flexion angles under varying loading conditions are studied.

Keywords— ***Knee Joint, Mechanical Behavior, Design, Analysis, Solid Works***

I. INTRODUCTION

The knee joint is the largest joint in the body and is very complicated, which consisting of four bones and an extensive network of ligaments and muscles. Injuries to the knee joint are amongst the most common in sports activities and understanding the anatomy of the joint is fundamental in understanding any subsequent pathology. The knee joint is the connection between the thigh and leg. Three bones come together at the knee joint, and the knee is surrounded by four major ligaments. The knee joint surface is covered by a layer of smooth cartilage, and shock-absorbing meniscus. The developing of solid models of the knee is one of many steps involved in using engineering principles to solve medical problems within the human knee joint. One such problem in the knee joint is meniscal tearing. This research is specifically aimed at developing models to be later used in the analysis of knee joint. The knee is a complex, compound, condyloid variety of a synovial joint. It actually comprises three functional compartments, the femoropatellar articulation consists of the patella, or "kneecap", and the patellar groove on the front of the femur through which it slides and the medial and lateral femorotibial articulations linking the femur or thigh bone with the tibia, the main bone of the lower leg. The joint is bathed in synovial fluid which is contained inside the synovial membrane called the joint capsule.

The knee is made up of four main bones-the tibia (shin bone), fibula (outer shin bone) and patella (knee cap).The main movements of the knee joint occur between the femur, patella and tibia. Each are covered in articular cartilage which is an extremely hard, smooth substance designed to decrease the frictional forces as movement occurs between the bones. The patella lies in an indentation at the lower end of the femur known as the intercondylar groove. At the outer surface of the tibia lies the fibula, a long thin bone that travels right down to the ankle joint.

Understanding of the interacting forces among the components of the human knee during daily physical activities is of prime importance to prevent injuries on this articulation. In addition, the knowledge of such forces is fundamental in the proposal of prosthesis design, rehabilitation, and muscular strengthening. Besides the experimental studies, mathematical and computational models of the knee joint have been developed to predict the approximated biomechanical behavior of individual fibrous tissue and of the entire articulation.

While the mathematical models of the knee joint can be useful to predict forces and stresses in individual structures of the articulation, as well as to estimate its kinematics, validation of such models is a challenging task. It is complicated to make a computational model of the knee that accurately predicts the response and movements of the articulation as it is resembled by experimental methods.

II. SOLID MODELING AND ITS APPLICATIONS IN MEDICINE

A solid model is a three-dimensional mathematical representation of an object. Solid models began development in the 1970s to facilitate the complete automation of the manufacturing of man-made parts. Today, solid modeling is a large field, encompassing virtually all aspects of engineering. When solid modeling is used to represent parts (three-dimensional reconstructions) that are already in existence, rather than to design parts, it is referred to as reverse engineering.

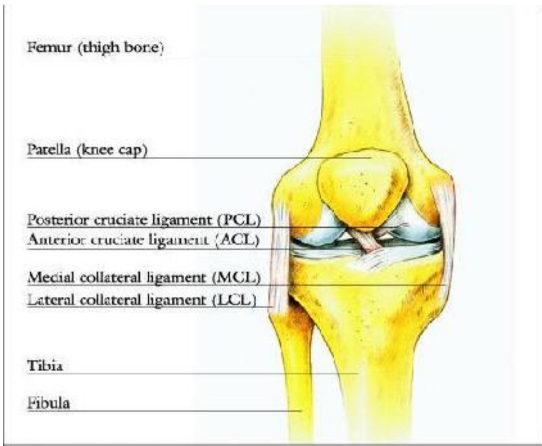
Recent advances in computing technologies both in terms of hardware and software have helped in the advancement of CAD in applications beyond that of traditional design and analysis. CAD is now being used extensively in biomedical engineering in applications ranging from clinical medicine customized medical implant design to tissue engineering. This has largely been made possible due to developments made in imaging technologies and reverse engineering techniques supported equally by both hardware and software technology advancements. The primary imaging modalities that are made use of in different applications include, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), optical microscopy, micro CT, etc. each with its own advantages.

In recent years, solid modeling has been used extensively in medical applications. Creating solid models of hip prosthetics has led to an improved prosthetic hip design and using solid models for visualization purposes has aided people with back pain. In virtually every field where engineering meets medicine, solid modeling can be found.

III. KNEE JOINT ANATOMY AND FUNCTIONALITY

The knee is classified as a compound synovial joint, which means that it has multiple articulating surfaces and is enclosed in a synovial fluid. A basic anatomy of the knee is shown in figure. The bones in the knee include the femur, the tibia, and the patella and the four ligaments that are anterior cruciate ligament, posterior cruciate ligament, medial collateral ligament, lateral collateral ligament.

The knee joint joins the thigh with the leg and consists of two articulations: one between the femur and tibia, and one between the femur and patella. It is the largest joint in the human body and is very complicated. The knee is a mobile trocho-ginglymus (i.e. a pivotal hinge joint) which permits flexion and extension as well as a slight medial and lateral rotation. Since in human body the knee supports nearly the whole weight of the body. However, the femur and the tibia are structurally predominating. The patella is used to provide mechanical advantage to the joint. The knee moves on four articulating surfaces, the medial and lateral condyles of the femur and tibia. Articular (hyaline) cartilage is found on the opposing surfaces of these condyles.



Right leg, showing all 4 key knee ligaments

IV . PROJECT PROPOSAL

Knee joint is one of the main joint in the body which helps in stability of the body. Due to frequent use, the knee joint is susceptible to injury and damage that can cause knee joint problems. When the knee joint fails, it should be replaced with the artificial one. In this project, reconstruction of 3D anatomical CAD model of human knee joint using patient specific cadaver bone and analysis is carried. The model is a geometric non-linear contact path-dependent model that includes friction between bodies, which let us understand its structural mechanical behavior and difference between results obtained from linear analyses and non-linear analyses are compared. Mechanical properties of bones vary, in general, according to age, weight, gender, and feeding habits of the subject under analysis.

	Femur	Tibia	Menisci
E_x	6.1e3 MPa	6.9e9 MPa	0.2e2 MPa
E_y	8.692e3 MPa	8.5e3 MPa	1.4e2 MPa
E_z	1.2793e4 MPa	1.84e4 MPa	0.2 MPa
PR_{xy}	0.38	0.49	0.2
PR_{yz}	0.24	0.14	0.3
PR_{xz}	0.22	0.12	0.2
Gxy	2.361e3 MPa	2.4e3 MPa	6.9565e3 MPa
Gyz	4.0411e3 MPa	4.9e3 MPa	0.807e2 MPa
Gxz	3.588e3 MPa	3.6e3 MPa	3.913 MPa

Mechanical Properties Of Femur, Tibia And Menisci

Mechanical properties of Patella

	Compact
Ex	6.91e3 MPa
PRxy	0.3

Ligament properties

Young's modulus	303 MPa
Poisson's ratio	0.28

Ligaments cross sectional area mm^2

Anterior Cruciate Ligament (ACL)-44
Posterior Cruciate Ligament (PCL)-60
Medial Collateral Ligament (MCL)-18
Lateral Collateral Ligament (LCL)-25

Biomechanics of Knee Joint

The human body, a part of all its other function is a mechanical mechanism and a structure, since it transmits movement and forces. As a structure its elements may be subjected to forces and suffer stress and strain. Biomechanical analysis has been made for many years, and it has been a huge effort to analyze theoretical and structural behavior of components of the human being when subjected to a force.

Biomechanics (the science of the action of forces on the living body) can be somewhat intimidating to the uninitiated. Nevertheless, an understanding of a few key concepts can bring a new appreciation to the study of knee ligaments. This branch of biomechanics deals with the relationships between externally applied loads and the resulting internal effects on a material". and strain can be represented on a stress-strain curve. The slope of this curve (Young modulus of elasticity on E) represents the stiffness of a material -that is, its ability to resist deformation. The tensile strength of a ligament is the maximum stress that the ligament can sustain before failure. Biomechanics includes bioengineering, the research and analysis of the mechanics of living organisms and the application of engineering principles to and from biological systems. By applying the laws and concepts of physics, biomechanical mechanisms and structures can be simulated and studied. The human knee joint is having 6 degrees of freedom. They are three rotations and three translations.

Kinematic of knee joint

Kinematic is important to the understanding of the form and function of the knee. The main objective in the knee ligament reconstruction is the reconstruction of joint stability with normal joint kinematics. Thus, we must have an understanding of the role of the ligament damage on this motion. Motion of knee can be described with the use of six degrees of freedom. They are THREE rotation (flexion-extension, internal-external rotation, and varus-valgus angulations) and THREE translation (anterior posterior, medial lateral and cephalad caudad).In knee motion primary translation and rotation occur in the sagittal plane and are coupled with obligatory rotation about another axis.

V. SolidWorks

SolidWorks is an incredibly powerful tool in both mechanical and optomechanical design. As a solid modeling program, it can be used throughout the design process. SolidWorks can be used to create rough models to provide the engineer component perspective and a feel for how parts will fit together. It can also be used as a very detailed design tool where every piece of a design down to the fasteners is included. The weights of these components can also be specified to create a very accurate representation of what the actual part will look like. In this particular example, a rough solid model of a compact security camera will be created. The camera, whose model will be useful for component layout in a larger assembly, SolidWorks is a Parasolid-based solid modeler, and utilizes a parametric feature- based approach to create models and assemblies. Parameters refer to constraints whose values determine the shape or geometry of the model or assembly. Parameters can be either numeric parameters, such as line lengths or circle diameters, or geometric parameters, such as tangent, parallel, concentric, horizontal or vertical, etc. Numeric parameters can be associated with each other through the use of relations, which allow them to capture design intent.

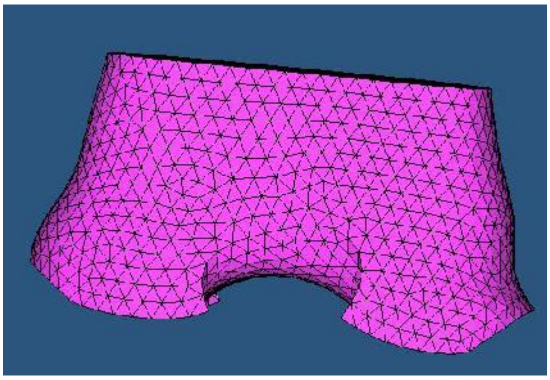


Fig-2: Finite element model of Femur

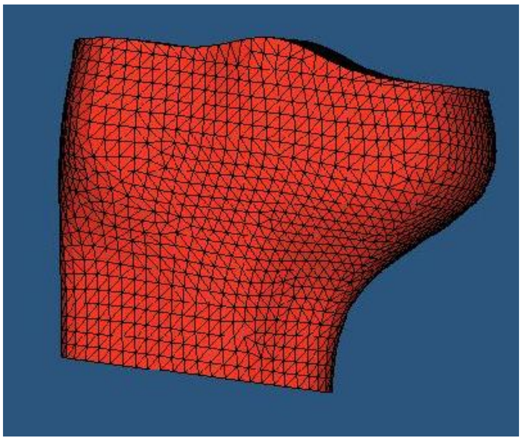


Fig-3: Finite element model of Tibia

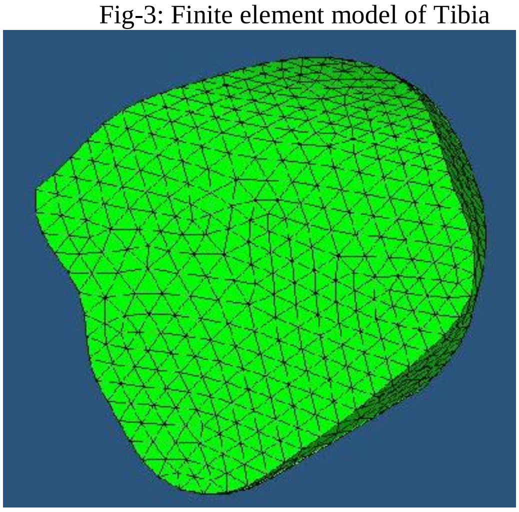


Fig-4: Finite element model of Patella

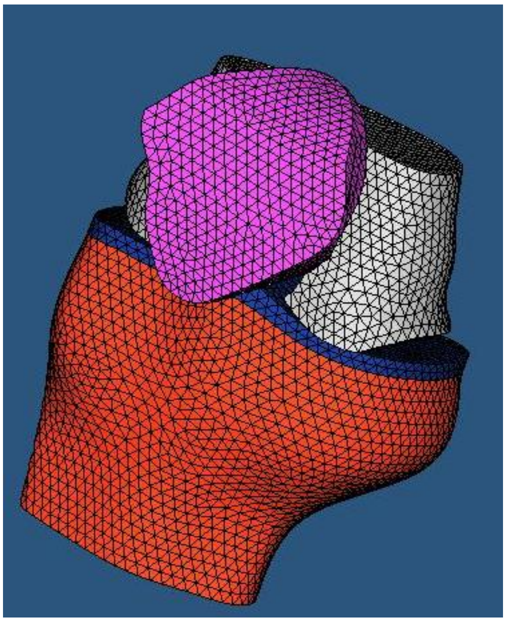


Fig-5: Finite element model of knee joint

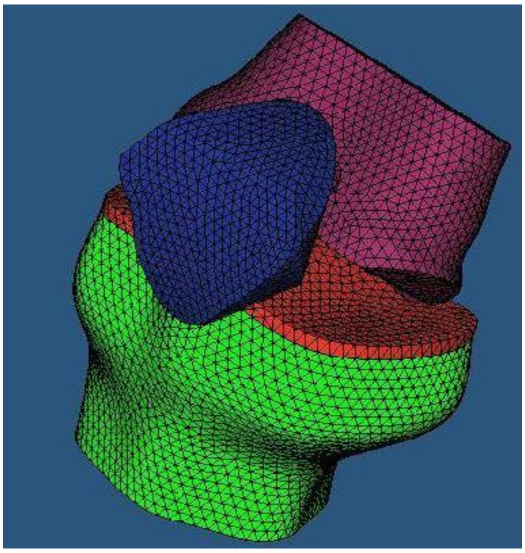


Fig-6: knee joint with flexion angle 45^0

VI. RESULTS AND DISCUSSION

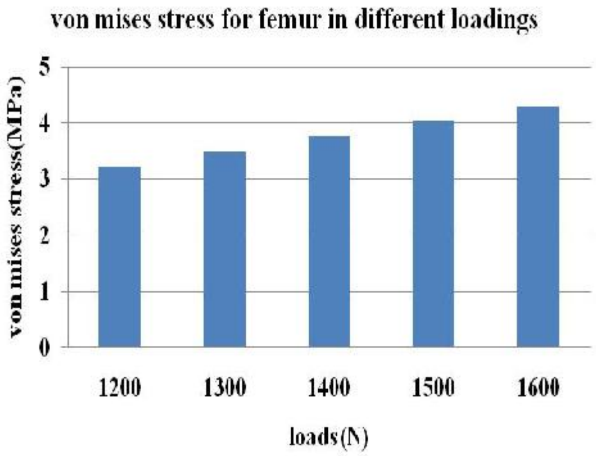
Stress Distribution for Individual Bones for different loads

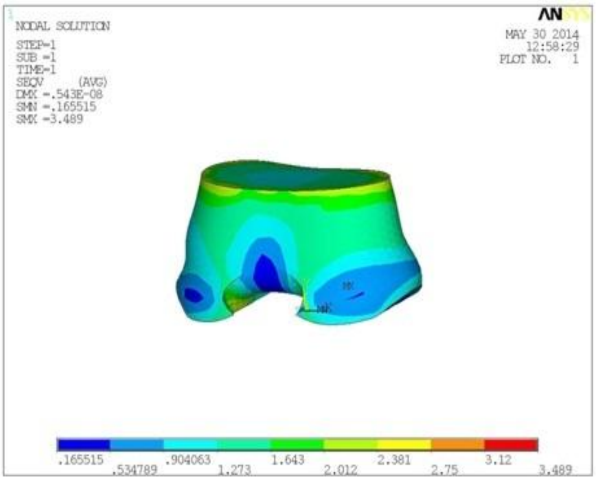
Femur Model

A load of 1200N, 1300N, 1400N, 1500N and 1600N was applied on the individual bones of femur and tibia. And the same load was applied to the total

knee joint and for the flexion angle 45^0 angle and the load distribution was observed.
From the above graph we can observe that at 1300N the bone can withstand the load.

As the load increases from 1300N to more the bone gets deformed gradually. If it increases the bone may deform its shape causing breakage of the bone. The distribution of load was as follow in the model of 1300N.

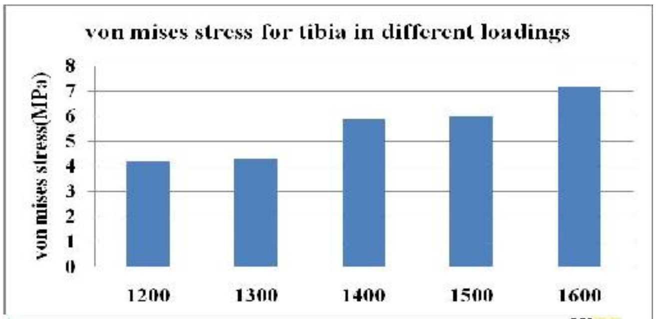


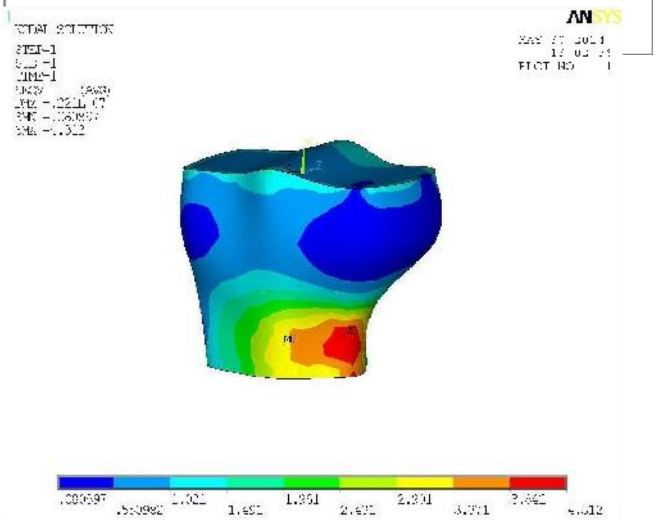


Tibia model

A load of 1200N, 1300N, 1400N, 1500N and 1600N was applied on the tibia bones. And the same load was applied to the total knee joint and the load distribution was observed. From the above graph we can observe that at 1300N the bone can withstand the load.

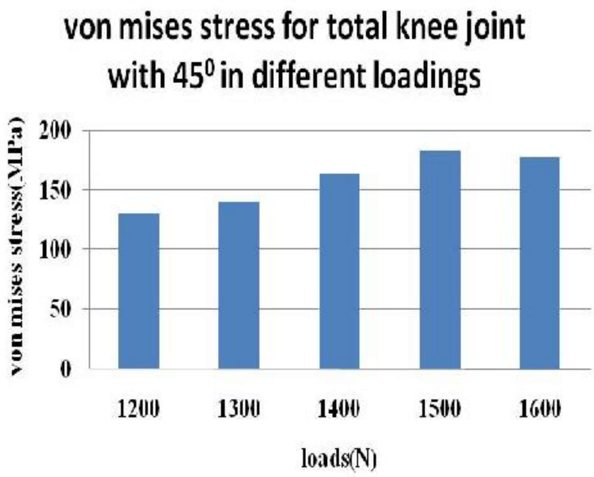
As the load increases from 1300N to more the bone gets deformed gradually. If it increases the bone may deform its shape causing breakage of the bone. The distribution of load was as follow in the model of 1300N.

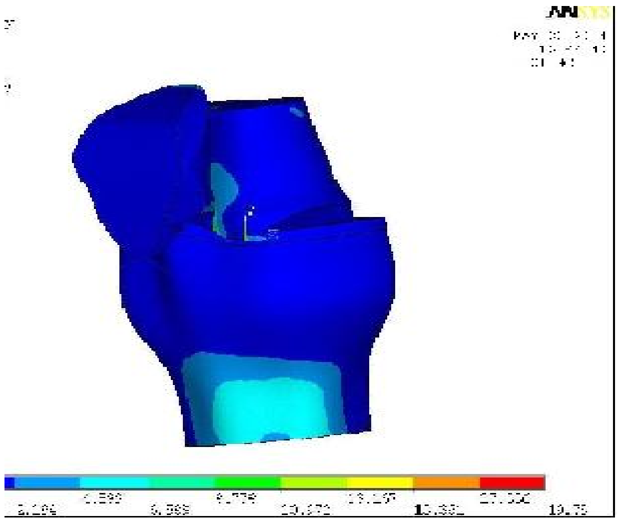




Total knee joint

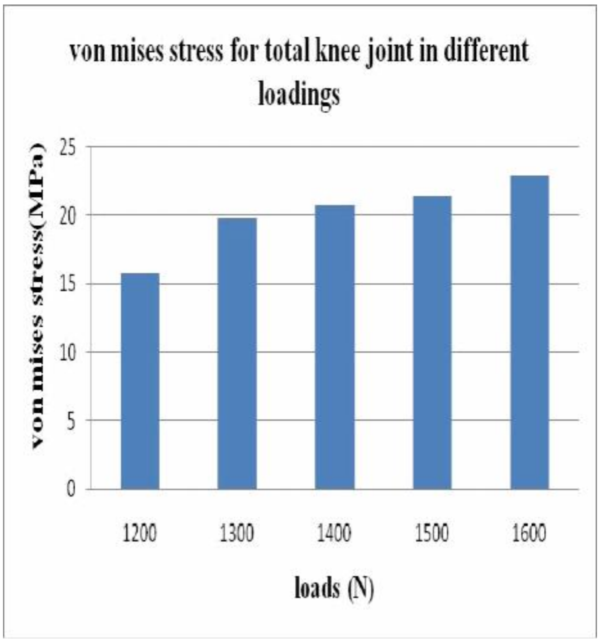
A load of 1200N, 1300N, 1400N, 1500N and 1600N was applied on the tibia bones. And the same load was applied to the total knee joint and the load distribution was observed.

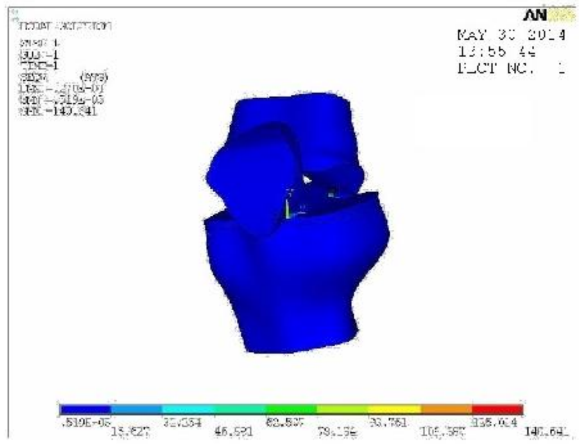




As the load increases from 1300N to more the bone gets deformed gradually. If it increases the bone may deform its shape causing breakage of the bone. The distribution of load was as follow in the model of 1300N.

Knee joint with flexion angle 45^0





VII. CONCLUSION

The anatomical CAD model was model in SolidWorks and Biomechanical Behavior of the Knee Joint analysis are carried out using Ansys. The knee joint models (Femur, Tibia and Patella) are modeled and the FEM analysis of individual model is carried out for different loading conditions and for total knee joint and with a flexion angle, the stress distribution is studied. In this work 45^0 flexion angle is considered. From the studies we can conclude that at 1300N load the knee joint can withstand. If the load increases gradually the deformation will takes place and leads to failure.

For the future scope, finding out all the possible flexion angles for the knee of the specified patient age group and analysis can be carried out for various stress distribution in the knee joint.

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