Estimation of stress and strain of knee joint using finite element analysis

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Abstract. In the present paper, finite element analysis of the knee joint is performed for stress and strain estimation of the knee joint for osteoarthritis patients. Osteoarthritis (OA), called the wear and tear arthritis is commonly occurring arthritis wherein a gradual loss of cartilage from the joints are observed. This leads to the joint bones rubbing quite close against one another with less amount of shock-absorbing done by the cartilage causing pain, stiffness, swelling, decreased movability and bone spur formation can be observed. It is mostly observed in patients above 45 years old, but weight and gender are also some of the factors forcing a quick onset of the disease. Using modelling software Blender, a solid model is made of the bone component, namely tibia, fibula, femur and patella as well as Ligaments and cartilages. Using finite element simulation software, analysis is done to determine the level of stress under various forces on the joint. The knee joint experiences a maximum stress and strain of 2.352 MPa and 0.02454 respectively which are within safe static condition. The study can be further extended to predict the danger of failure for the patients having osteoarthritis conditions which in turn will help to take a preventive measure for the knee joint.

Keywords: Osteoarthritis; Finite element simulation; Knee joint

1. Introduction
The knee joint is often associated with a high incidence of injuries and osteoarthritis considering it being one of the most heavily loaded and mobile joints in the human body. A lot of work has been done into biomechanical processing, its modelling, and its computation over the last few years. 3d models generated through computer present a standard scheme for studying parameters like stress distributions for different geometries and kinematics. Finite Element Method is one of the techniques used extensively to study its biomechanics. Due to its location and its distance, the joint below the body’s center of gravity, a very high compressive load as much as 6 times the body weight acts on the tibiofemoral joint.

1.1. Knee Joint
Figure 1 shows the representative picture of the knee joint as per anatomy [1]. In humans as well as all the remaining primates, the knee acts as a joint between the thigh and the leg and it consists of two joints: one between the patella and femur (patellofemoral joint) and one between the tibia and femur (tibiofemoral joint). It is the most important joint within the physical body. The knee may be a modification of the hinge joint, which allows extension and flexion, also a little internal and external rotation. By articulations between the femur, patella and tibia, the knee joint is formed. The knee works as a joint between the thigh bone (femur) and the shin bone (tibia). By working as a connection between the anterior cruciate ligaments (ACL) prevents back skidding of the femur on the tibia and vice versa.
Knee bones and the leg muscles, Tendons helps to move the knee. [1] Ligaments join the knee bones and supply stability to the knee:

- The posterior cruciate ligament (PCL) prevents the forward sliding of the femur on the tibia and vice versa.
- The lateral collateral ligaments (LCL) and medial collateral ligaments (MCL) block the side to side sliding of the femur.

Along with the two cartilage, medial and lateral menisci, shaped like a C are also present which provides shock absorption between tibia and femur. Apart from it many bursae, helps the knee to glide through smoothly. The knee comprised of four main substances namely, bones, cartilage, ligaments and tendons. Other than that, it also has the muscles which cause the knee to manoeuvre are connected with the bones by tendons. These Knee muscles help with the overall flexion/extension movements, Hamstrings for flexion, and the quadriceps for knee extension. There are also many muscles around the knee that support its function [1]

Fig. 1. Anatomy of the knee joint [1]

1.2. Rapid Prototyping of Knee Joint

Due to the absence of anthropometric data of Indian knee and lack of much research, today all the joint replacements in India are carried out using standard size parts selected from a range of sizes provided by the manufacturers based on anthropometric data of the western population. Possible complication due to this includes prosthesis breakage, blood clotting, wear dislocation, loosening, infection, and nerve injury. Apart from the above-mentioned problems that are present universally with the implantation of these prostheses worldwide, the use of these in Indian populations suffer from additional problems. Nowadays, the knee of a knee replacement patient can be cut in such a manner that the new knee (the implant) fits exactly to the bone. By using a cutting block specific to the patient, a patient's joint bone is cut in such a manner that it is exactly like the inside shape and the implant fits like building blocks. X rays, CT scans, MRI, the joint’s 3D image of the patient is transferred to a software which then on the basis of where it needs to be cut, make marks on this bone image. A pattern is then formed in a CAD software, which can save the trouble of taking all the measurements. It is connected at the joint while the surgery is being carried out, and then the bone is directly cut through the gap in the pattern. The physical model of a part is created directly from a 3D CAD model by rapid prototyping. The materials like ceramics, ABS, fusing powdered thermoplastic materials, liquid resin, investment wax, etc. are used. The Rapid Prototyped primitives provides a life-size model which can later be handled, analysed, and used in the future.

1.3. Osteoarthritis.

It is the most frequently occurring type of arthritis. Although it occurs mostly in people above the age of 45, it can occur even in young people. Other factors like,

- Weight- Every kg of weight gained adds 3 to 4 kgs of extra weight on the knees.
Heredity- Sometimes genetic mutations might increase the chance of getting osteoarthritis of the knee or it may even be due to shape abnormalities of the knee joint bones, which were inherited.

Gender- Women are more susceptible to osteoarthritis of the knee.

Repetitive stress injuries- Certain occupations comprising activities stressing the joint are more likely to give osteoarthritis of the knee to the person.

Athletics- Athletes are quite prone to injuries hence their chance of getting OA increases.

Other illnesses- Patients of rheumatoid arthritis, are also more likely to develop osteoarthritis. Iron overload, excess growth hormone and certain metabolic disorders might also increase the risk of osteoarthritis.

Hence the appropriate understanding and assessment of knee joint biomechanics are accordingly vital to enhance the anticipation and treatment of related issue and wounds. Finite element models (FEM) is the solution to this problem. FEM has been appeared to give knowledge into the mechanical properties of biological tissues and the execution of living organs, diminishing cost.

Global Burden of Disease 2000 estimated that about 10% of the world’s populations who are greater than 60 years of age have symptomatic issues that can be attributed to OA. The COPCORD investigations in India for the year 2011 concluded that the rough occurrence of clinically diagnosed knee OA was greater in the urban (5.5%) than the rustic group of people (3.3%). The major causes are increased in Contact pressure or modifications in knee joint structure and contact area.

2. Literature Reviewed

Barbara Postolka et al [2] explained how the most critical conditions for the surrounding soft tissues are known to occur during high-flexion activities by providing evidence on the location of the centre of rotation during multiple complete cycles of different gait activities. V. Ashwin Kumar et al [3] studied the biomechanics of Osteoarthritis knee and explained how diagnosis based on geometrical measurements might be helpful in diagnosing at an early stage by estimating the articular cartilage thickness of the knee. Pierre-Jean Arnoux et al [4] explained that due to non-homogeneity in biomedical materials, even for a small sample, their experimentation is difficult. Finite element analysis helps to overcome this problem by enabling to test several times the same sample for several variables, or various boundary conditions. M Z Bendjaballah, et al [5]. They explained how excessive Varus-Valgus stresses not only damages the LCL and MCL, but the ACL as well. Thus, compromising its stability. Nikolaos K. Paschos, e. al [6]. They explained a direct connection between the failure patterns in the load-elongation curves and the macroscopic sequence of events during ACL failure. T. Ingrassia, et al [7] They compared two different total knee prostheses and found out that the central region is the most stressed region of the two prostheses, both acting as a cam or as a guide. M. Marieswaran et al[8] They explained that both the rotation of the tibia (with respect to the femur) and the femur’s translation over the tibia (forward/backward) are involved in flexion and extension of the knee joint. They explained the variation of knee joint’s centre of rotation (CoR) with respect to the flexion angle and also about the direction of various forces acting. R S Jones FRCS et al [9] They measured the strength of femur-anterior cruciate ligament-tibia complex in a physiological condition by applying forces on the tibia’s anterior in two age groups and found out that for people above 60 years of age, at high load cycles, there is a large increase in stiffness with increase in less amount of load.
3. Methodology

A 3-D model of a 24 years old woman is created using MRI scans. The model consists of the components: femur, tibia, fibula, meniscus, cartilage (both femoral and tibular) and the ligaments: anterior cruciate ligaments (ACL), medial collateral ligament (MCL) and lateral collateral ligament (LCL).

This model is imported into an FEA solver. In Hypermesh software, Optistruct profile is being used here. After importing the model and completing the appropriate geometric cleanup, Boolean operation is used to create node to node connection. A 2D mesh is created and further a 3D tetra-mesh is created throughout the solid. Further non-linearity in material and geometry is used.

Table 1 shows the material properties of all the components. Bones being plastic in nature, non-linearity in material is used for them and thus nonlinear quasi-static analysis is used and its non-linear material properties are given in table 2. Table 3 indicates the force acting on various parts of the knee joint applied during analysis. Figure 3 shows the location of forces applied and figure 4 shows the boundary conditions applied for the analysis purpose. The femur is fixed by applying boundary conditions on its hip end and forces are applied. Finally, the file is imported in the Optistruct format and then solved in the Optistruct solver.

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**Table 1** Material properties of components [10, 11, 13, 14, 17].

| Material  | Young’s modulus (MPa) | Poisson’s ratio | Density (ton/mm$^3$) |
|-----------|------------------------|-----------------|----------------------|
| Bones     | 17400                  | 0.3             | 1.708583e-9          |
| Ligament  | 1500                   | 0.3             | 1.84086e-9           |
| Meniscus  | 59                     | 0.45            | 1.10231e-9           |
| Cartilage | 12                     | 0.45            | 1.26765e-9           |

**Table 2** Non-linear Material properties of bones

| Material | Yield stress (MPa) | UTS | Max strain @UTS |
|----------|--------------------|-----|-----------------|
| Bone     | 114                | 135 | 0.0132          |

**Table 3** Values of various forces on knee joint [9, 12].

| Forces               | Values (N) |
|----------------------|------------|
| Tibiofemoral force   | 1800       |
| Patellar Tendon force| 900        |
| Hamstring Muscle force| 450       |
| Gastrocnemius Muscle force| 450     |
| Ground Reaction force   | 730        |
4. Results and discussions

The bone is made of a protein named collagen and a mineral calcium phosphate. Collagen provides a soft framework while the mineral provides strength. This in turn makes the bone strong and flexible. Thus, allowing it to withstand various stress conditions. Various forces and values are mentioned in Table 3. Analysis of the 3D CAD model was performed in Altair HyperWorks software. Optistruct solver was used to perform the analysis. The contour plot of von Mises stress and strain was obtained. Figure 5(a) and figure 5(b) show the contour of von Mises stress and strain respectively for the knee.

On completion of the analysis, a maximum stress of 2.352 MPa and a minimum stress of 1.675E-11 MPa is observed. Also, a maximum element strain of 0.02454 and a minimum strain of 8.341E-16 is observed. The analysis is performed as static analysis and it indicates the knee joint is safe under static load (permissible ultimate tensile stress 6 Mpa \cite{18} and strain are 0.6\cite{19}). The material and geometrical
properties of the knee joint is that of a young person hence the damage is under the limit of permissible value. As the people grow older, there will be further degradation in material properties for example, the bone gets more brittle and cartilage gets wear down. These critical conditions can be further analyzed using finite element simulation.

5. Conclusions
From the present paper, it can be concluded that osteoarthritis is a very common disease and the stresses and strain can be obtained using finite element analysis. Due to the bone geometry, the center of rotation keeps changing and thus the line of action of the forces applied also keeps changing. All these factors need to be considered before doing the simulation. Finite element analysis is one of the important theoretical techniques to simulate the conditions several times with several variables like velocity, weight, etc. Thus, providing us a more reliable solution. With the advancements in the medical imaging techniques, and reconstruction of MRI models, there has been an expansion in the possibility to incorporate specific tissue morphology and boundary conditions into in vivo subject-specific models. For obtaining better results using the FE model, an accurate and suitable representation of the geometry and assigned material properties is essential. Along with it, realistic simulation of how they interact, which boundary conditions and constraints needs to be applied and lastly validation against experimental data is also required

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