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Finite Element Analysis on Knee joint for Knee OA Patients

*** K. Thienkarochanakul, D. Hiscocks and A.A. Javadi**

Department of Engineering, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF
kt301@exeter.ac.uk,

ABSTRACT

Understanding the mechanical behaviour of the knee joint is essential in the design of treatment for patients with knee OA or people with knee injuries. Previous research has often overlooked the stresses and strains in the cartilage soft tissue that causes pain, while walking or bending legs, as a result of the rubbing between the upper leg bone (Femur) and the lower leg bone (Tibia). Simulating a human knee joint using the Finite Element Method can show not only how much stress the knee joint cartilage takes due to human bodyweight, but the distribution of stress throughout the cartilage as well. This paper presents a 3D FE model of a knee joint, created from geometry obtained from a human CT scan. The effect of OA has been modelled by halving the Young's Modulus of OA cartilage, whilst maintaining the same boundary conditions. A comparison of OA knee & healthy knee has been completed, and results show that the stress in the cartilage increases by 1Mpa as a result of OA. Good agreement was found in both results, and the location thereof, between presented and other published work.

Keywords: *knee osteoarthritis (knee OA); cartilage; orthosis; FEA*

1. Introduction

Knee anatomy and functions

Human walking is the result of a complex process involving the brain, spinal cord, peripheral nerves, muscles, bones and joints [9]. Human walking requires the coordination of multiple muscles and joints to simultaneously move the legs in a periodic pattern, support body weight and maintain dynamic stability. Coordination may be simplified by taking advantage of the passive dynamics of the legs which can perform all of these functions automatically [9].

Knee diseases –OA

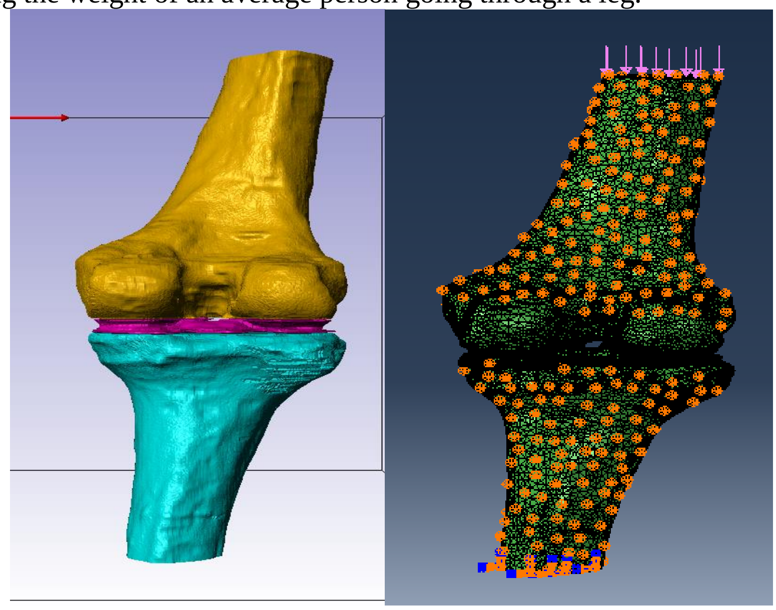
Osteoarthritis (OA) is a disease which influences the body joints. The most common affected joints are in the hands, spine, knees and hips. Knee OA is a degenerative, painful disease that if left untreated it can have crippling effects on those affected. Unfortunately, nearly every aging person develops knee OA to some extent [5]. OA causes damage to the articular cartilage (protective surface of the knee bone) and mild swelling of the tissues in and around the joints. OA is one of the most common causes of disability in the world. It is regarded as a whole joint disease with a multifactorial aetiology, including increased mechanical stress, ligament derangements, cartilage degradation, subchondral bone changes and muscular impairments [10]. However, not all knee pains are associated with OA, there are other diseases e.g. patella tendonitis, chrondromalacia, Osgood-Schlatter disease or gout that can also cause pain to the knee, either acute or chronic [6]. In addition, obesity and lower limb misalignment have also been associated with increased risk for knee OA [8]. In OA patients, the cartilage (connective tissue) between the bones gradually degrades leading to painful rubbing of bone on bone in the joints. Sitting between the upper and lower leg bones at the knee joint are rubbery pads of tissue called menisci. These cushion the bones, acting as shock absorbers. The menisci can become worn as one gets older, and are commonly the reason for knee pain in middle-aged people. A meniscus can also be torn after suddenly twisting the knee joint, resulting in pain, swelling and occasionally the locking of the knee. The illness is caused by muscle weakness, ligaments, nerves, degenerative bone disease or cerebrovascular disease. Current treatments include medical procedures or surgical treatment including physiotherapy. The damage of these symptoms may cause tearing in the cartilage soft tissue due to the force of body weight, resulting in activities such as walking,

running or squatting causing great pain to the patient. In some cases, rehabilitation may be impossible and some older patients with OA, not fit for surgery, will continually suffer in pain.
A number of devices exist that assist walking and provide knee pain relief, ranging from staff to robotic devices. Several knee braces are currently available on the market that not only deal with OA but also with other diseases or injuries. Some braces may not be comfortable to wear or slim enough to put under dress. Furthermore, as the complexity of the devices increase, so too does their cost to the extent that some are unaffordable to some patients. The main focus of the research undertaken is towards the design of a new knee bracing system, which allows effective control of the transfer of forces through the knee joint. This can reduces the amount of force that is transferred through the joint and hence reduce the pain and improve mobility. The study of knee anatomy and the mechanical behaviour of knee is an important part of this research.

This paper presents the study of mechanical behaviour of knee joint, in order to better understand the function and behaviour of human knee joint and its load bearing mechanism. This will allow the distribution of stresses in the cartilage to be determined, and in turn, the effects of OA on the stress distribution throughout the cartalage to be assessed.

A finite element model of a knee joint is developed and analysed. The model of a genuine human knee joint is constructed from a CT scan, using a digital imaging suit, ScanIP software from Simpleware Ltd. Three masks are created to define the femur, cartilage and tibia shown as yellow, purple and blue respectively, in Figure 1a. The constructed model is then analysed using the finite element code ABAQUS 6.13-1.

Boundary conditions and material properties are both applied based on published information [1, 3]. By way of boundary conditions, both displacements and rotations at the bottom surface of the tibia are fixed in all directions. The displacement is fixed for the femur and tibia in Y direction, shown in Figure 1b. Different material properties are considered for bone and cartilage, however they are both assumed to be linear elastic. The Young's moduli of bone and cartilage are considered as E_{Bone} = 18.6 GPa, and $E_{Cartilage}$= 12 MPa with Poisson's ratios of v_{Bone} = 0.3 $v_{Cartilage}$= 0.46 respectively. The property of the OA cartilage was redefined with a reduction of 50% of $E_{Cartilage}$, $E_{OACartilage}$ = 6 MPA and Poisson's ratio $v_{OACartilage}$= 0.49, as used in [10]. The geometry of the model, loading and boundary conditions are shown in Figure 1b. Contact elements are used in the model to tie the cartilage to the femur and tibia. Quadrilateral (8-noded) elements and structured meshing are used in the discretisation of the domain. The system is subjected to a vertical load of 392 N, (pressure of 0.3 MPa), representing the weight of an average person going through a leg.



(a) (b)

Figure 1 (a) 3 Masks created with ScanIP, (b) Geometry, loading and boundary conditions

2. Result and Discussion

Figure 2 shows the geometry before and after loading, in the healthy knee model. The model is not perfectly aligned, instead it is skewed (shown in Figure 2a), and hence it is deflected by the loading.

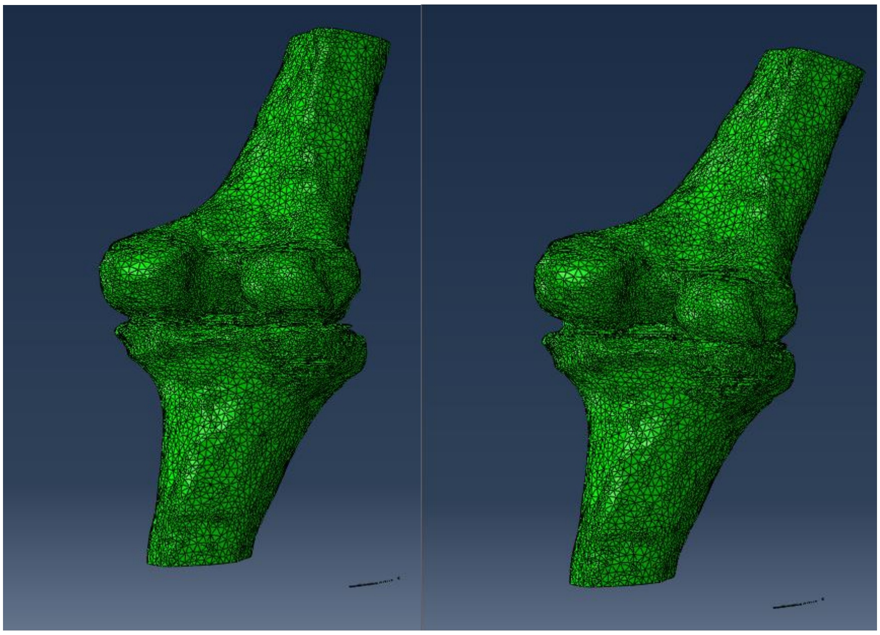
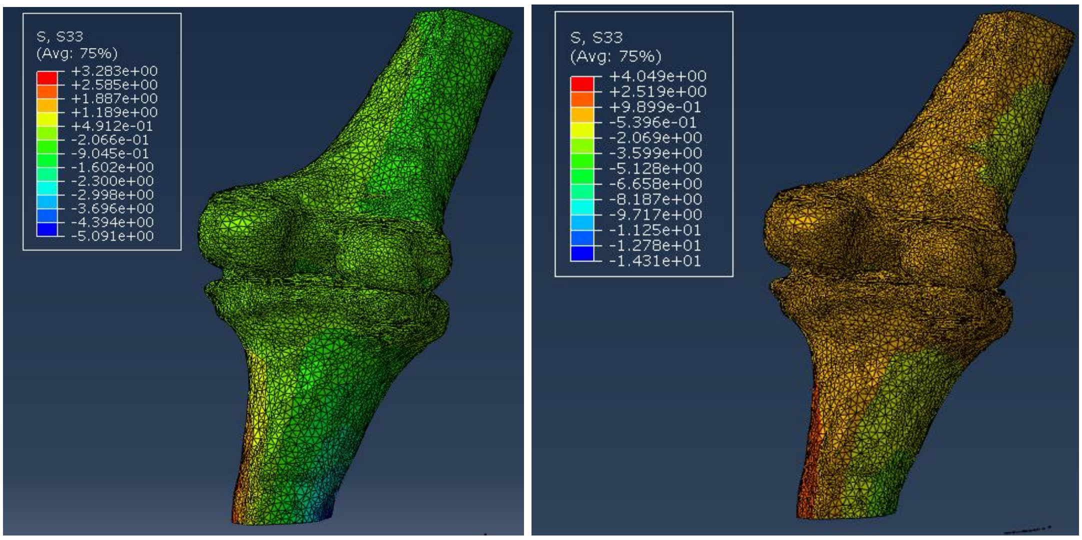


Figure 2 (a) unloaded geometry, (b) deformed geometry

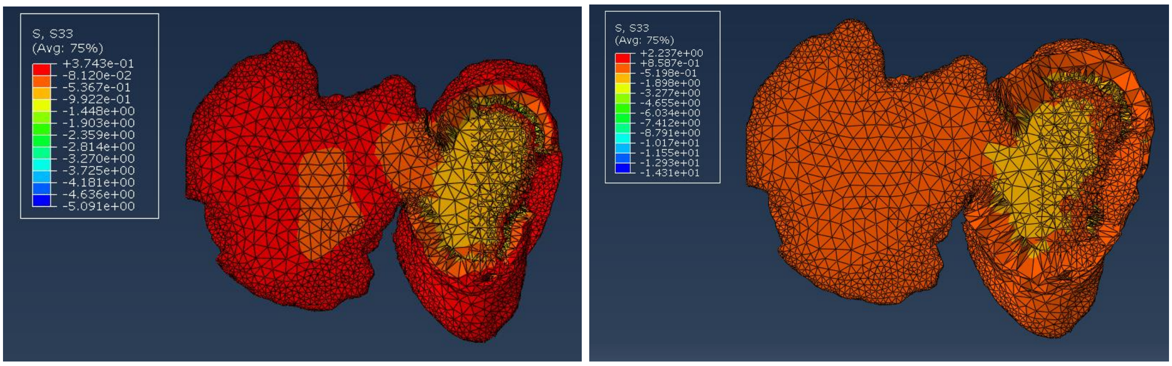
The results of the healthy and OA knees are shown in Figures 3a and 3b respectively. A similar stress distribution is found in both cases; however a difference in the maximum stress of 1 MPa is recorded in the OA case. This is due to the weakened cartilage collapsing between the two bones.



(a) **(b)**

Figure 3 (a) Deformed Healthy knee, (b) Deformed OA knee

Figure 4 shows the distributions of vertical stresses and deformations in the cartilage, for both healthy (4a) and OA knee joints (4b). In both cases, there is an area of high stress in the right hand section, as a result of the off – cantered model. This is a result of the femur and tibia colliding and compressing the cartilage located between the bones.



(a) **(b)**

Figure 4 (a) Deformed Healthy cartilage, (b) Deformed OA cartilage

Strong agreement is found between the increase in stress (due to the onset of OA), and the location of the maximum stress, between these results and those published in [10]. Discrepancies can be assigned to differing material properties, boundary conditions and geometry. Moreover, the location of the maximum stress, and the stress distribution found in the OA cartilage matched that of [10]. Further work will aim to refine the model, and in particular the boundary conditions. The use of a 'slip' boundary condition will be investigated, to better simulate the knee joint, and a dynamic model will be developed, in order to study the effect of the gait cycle on the knee joint.

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