A Finite Element Study of Stress Distributions in Normal and Osteoarthritic Knee Joints

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Objective: *To study the stress distributions in normal and osteoarthritic knee joints using the finite element method (FEM).*
Material and Method: *Three normal and three varus knee joints are included in the study. Computed tomography (CT) images of the lower extremities are used to create 3D geometric models consisting of bones, articular cartilages, menisci, and knee ligaments. Each of the lower extremities includes the femur, tibia, fibula, and talus. Each 3D geometric model is adjusted to the normal standing configuration with the help of its corresponding 2D radiographic image. After that, 3D finite element (FE) models are created from the adjusted 3D geometric models. FEM is then used to obtain stress distributions on the articular cartilages. In the analysis, the displacements on the posterior calcaneal articular surface of the talus are fully fixed. A vertical concentrated force equal to the body weight is applied at the femoral head.*
Results: *In the normal knee joints, the maximum normal stresses on the articular cartilages in the lateral compartments are always higher than those in the medial compartments. In the varus knee joints, the opposite results are observed. However, in each normal knee joint, the stress distribution on the whole articular cartilage is moderately uniform. On the contrary, in each varus knee joint, comparatively high magnitudes of the normal stress are found on a large area of the articular cartilage in the medial compartment.*
Conclusion: *Varus knee joints have higher stresses in the medial compartments while normal knee joints have higher stresses in the lateral compartments. This pilot study shows that FE studies are comparable to cadaveric studies. FEM can be used as an alternative method for studying and examining knee joints of patients.*

Keywords: *Osteoarthritic knees, Stress distributions, Finite element method*

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Knee osteoarthritis is one of the major chronic diseases usually found in the elderly and also a main cause of disabilities(1-6). The knee osteoarthritis involves a degenerative process of the articular cartilage of a knee joint which leads to the loss of the articular cartilage. This degenerative process can be caused by obesity, physical activities such as kneeling and squatting, joint trauma, immobilization and hypermobility(1-4,6). The damage is more commonly found on the articular cartilage in the medial compartment(7-9), which subsequently causes medial joint space narrowing as illustrated in Fig. 1. For the normal knee joint, the knee joint spaces in the medial and lateral compartments are approximately the same(6) as also illustrated

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in Fig. 1. The narrowing of the knee joint space in the medial compartment results in the malalignment of the lower extremity called the varus alignment. On the contrary, the damage of the articular cartilage in the lateral compartment results in the opposite malalignment of the lower extremity called the valgus alignment. These two types of the lower-extremity malalignment are illustrated in Fig. 2(a) and 2(c). In Fig. 2(b), the neutral alignment indicates the normal physiologic valgus alignment(10,11).

In the engineering term, the damage of the articular cartilage can be considered as a progressive failure since the lower-extremity malalignment due to the damage of the articular cartilage leads to even more damage of the articular cartilage. It can be postulated that the initial causes of the knee osteoarthritis, such as obesity, physical activities and joint trauma, initially create the stress that is higher than normal on the articular cartilage in one of the knee compartments. This causes the damage of the articular cartilage in that knee compartment, which subsequently results in the malalignment of the lower extremity. This malalignment, in turn, keeps the stress on the damaged articular cartilage high and, as a result, the damage continues to grow. In order to better understand this self-reinforcing mechanism, it is desirable to investigate how stress distributions in normal and osteoarthritic knee joints are different. Several cadaveric studies have been performed to obtain stress distributions in knee joints with normal, varus, and valgus alignments(12-16). In these tests, a compressive load was applied to each knee joint and the normal stress on the articular cartilage was measured via pressure-sensitive films or pressure transducers. Since cadavers were used in these tests, it was not possible to reproduce the real alignments of the lower extremities that occurred when these humans were alive. In addition, each specimen included only part of the lower extremity that was close to the knee joint. As a result, the boundary conditions employed in the tests might not reflect the correct load-carrying conditions of the lower extremities.

A good alternative method that can be used to investigate stress distributions on the articular cartilages in osteoarthritic knee joints is the finite element method (FEM). The method is currently the most popular tool used for solving mechanical problems. FEM allows experiments to be performed numerically. As a result, it provides alternatives to those physical experiments that are prohibitively expensive or difficult to perform. Basically, if the geometry, boundary conditions and material constitutive laws of the domain under consideration are accurate, FEM is expected to yield accurate results. FEM has been used to evaluate the biomechanical behavior of various parts of the human body as well as various orthopedic implants(17-20). This study aims to utilize FEM to investigate stress distributions on the articular cartilages in normal and osteoarthritic knee joints of living humans. The osteoarthritic knees considered in this study include only varus knees, which are more commonly found than valgus knees. Anatomical whole-length

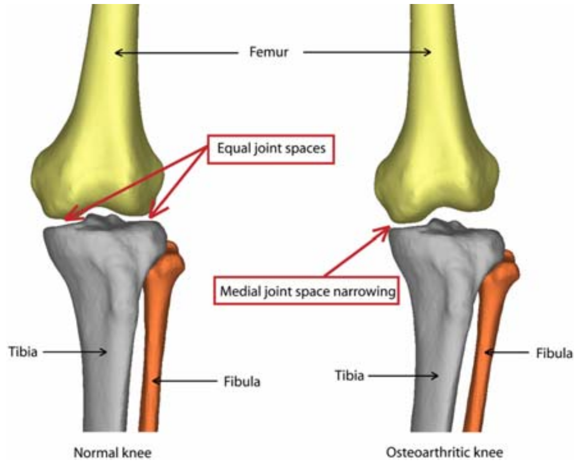

Fig. 1 Illustrations of normal and osteoarthritic knee joints

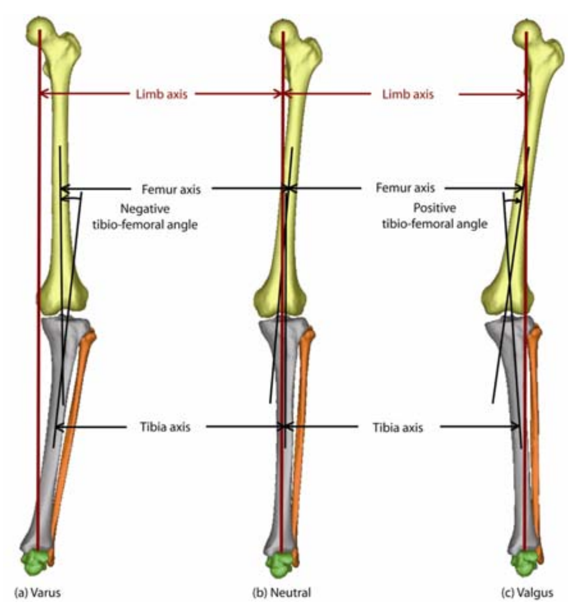

Fig. 2 Illustrations of (a) varus, (b) neutral, and (c) valgus alignments

finite element (FE) models of the lower extremities of living humans, consisting of bones, articular cartilages, menisci, and knee ligaments, are employed in the analysis. Computed tomography (CT) images are used in conjunction with 2D radiographic images to create the FE models. Using FEM as a tool for the investigation allows accurate alignments of the lower extremities during standing to be considered. In addition, the whole-length models ensure that accurate boundary conditions are applied. The obtained stress distributions on the articular cartilages in the normal and varus knee joints considered in this study are compared and the results of the comparison are discussed. In addition, the obtained results are also indirectly compared with the existing results found in the literature.

Material and Method

Three normal knee joints and three varus knee joints are included in the study. As aforementioned, CT images are used in conjunction with 2D radiographic images to construct the FE models of the whole-length lower extremities, consisting of bones, articular cartilages, menisci and knee ligaments.

Finite element models

The lower extremities of the human subjects are scanned with a Philips spiral CT scanner. After that, the CT images are imported into the Mimics program (Materialise NV, Belgium) and reconstructed to give 3D geometric models of the lower extremities. Each of the lower extremities includes the femur, tibia, fibula, and talus. The boundaries between different bones are located by using different threshold values of the Hounsfield unit (HU)[21,22]. Higher threshold values are used to extract the cortical bones of all diaphyses and the whole talus. Lower threshold values are used to locate the intramedullary canals as well as the epiphyses of the femur, tibia and fibula.

Since the CT images are not acquired during standing, it is necessary to adjust the alignments of the lower extremities of the 3D geometric models, obtained from the CT images, to the load-bearing alignments that occur during standing. This is done with the help of the 2D radiographic images taken with the normal standing postures. To this end, each 3D geometric model is superimposed onto its corresponding 2D radiographic image and the alignment of the lower extremity of the 3D geometric model is adjusted to the load-bearing alignment found in the 2D radiographic image. After that, the articular cartilages and menisci are modeled. In addition, the knee ligaments, including the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial cruciate ligament (MCL) and lateral cruciate ligament (LCL), are modeled to complete each of the final 3D geometric models.

The final 3D geometric models are then exported from the Mimics program as stereolithography (STL) files. Fig. 3 shows one of the final 3D geometric models. The FE meshes of all the models are then created in the Patran program (MSC Software, Inc., USA). In this study, only four-noded tetrahedral elements are used. The numbers of the elements employed in the six models range from 711,658 to 763,880. All analyses are performed in the Marc-Mentat program (MSC Software, Inc., USA).

Material properties

All materials are assumed to be homogenous, isotropic and linearly elastic. The material properties are shown in Table 1.

Boundary conditions

Each FE model is aligned in space in such a way that its limb axis is vertical. In the analysis, the displacements on the posterior calcaneal articular surface of the talus are fully fixed. A vertical concentrated force is applied at the femoral head. The magnitude of the force is set equal to the body weight to represent the one-leg standing condition. An example FE model including the boundary conditions is shown in Fig. 4.

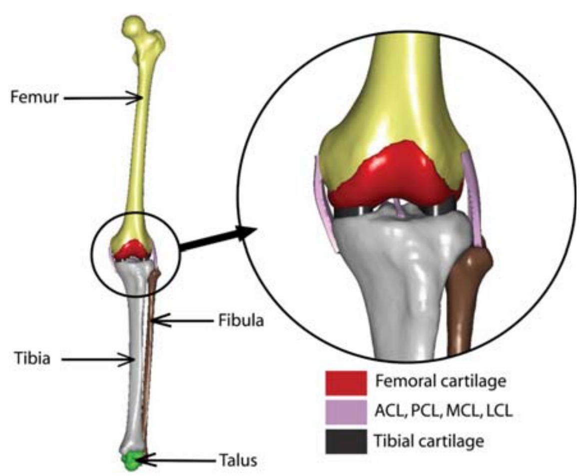

Fig. 3 A 3D geometric model

Results

Table 2 shows the details of the six lower extremities under consideration as well as their corresponding body weights. In addition, the table shows the maximum normal stresses found on the articular cartilages of these knees. It can be seen that, in the normal knee joints, the maximum normal stresses on the articular cartilages in the lateral compartments are higher than those in the medial compartments. In the varus knee joints, the opposite results are observed. Table 2 also shows the differences between the maximum normal stresses on the articular cartilages in both compartments, each computed as a percentage of the maximum normal stress on the articular cartilage in the lateral compartment. The differences of -25.35% to -47.62% and 141.80% to 407.58% are found in the normal and varus knee joints, respectively. It can be seen that, in the varus knee joints, the differences are very large. As shown in Fig. 5, the differences between the stress distributions in the normal and varus knee joints are apparent. In each normal knee joint, the stress distribution on the whole articular cartilage is moderately uniform. On the contrary, in each varus knee joint, comparatively high magnitudes of the normal stress are found on a large area of the articular cartilage in the medial compartment.

Table 1. The material properties[19,23,24]

Material	Modulus of elasticity (MPa)	Poisson's ratio
Femur, tibia and fibula		
Cortical bone	17,000	0.30
Cancellous bone	600	0.30
Talus	7,800	0.30
Articular cartilage and meniscus	12	0.45
Ligaments		
ACL	345.0	0.40
PCL	345.0	0.40
MCL	332.2	0.40
LCL	345.0	0.40

Discussion

From the obtained results, it is obvious that the varus alignment leads to higher magnitudes of the normal stress on the articular cartilage in the medial compartment. This is expected because, in the varus alignment, the knee joint moves outward from the limb axis in the direction of the lateral compartment. This displacement of the knee joint becomes a moment arm of the applied force at the femoral head. To maintain the equilibrium, the stress on the articular cartilage must be redistributed in such a way that there is an internal resultant moment at the knee joint to counter-balance the additional moment due to the displacement of the knee joint. For the varus alignment, it is necessary that the compressive stress on the articular cartilage in the medial compartment becomes larger. This behavior was also reported in the previous studies[12,16,25].

From Table 2, the differences between the maximum normal stresses on the articular cartilages in the medial and lateral compartments, each computed as a percentage of the maximum normal stress on the articular cartilage in the lateral compartment, range from -25.35% to -47.62% for the normal knee joints and

Table 2. The maximum normal stresses on the articular cartilages in the normal and osteoarthritic knees

Case	Alignment	Leg	Body weight [kg (n)]	Tibio-femoral angle (degree)*	Maximum normal stress		
					Medial (MPa)	Lateral (MPa)	Medial-Lateral (%) Lateral
1	Normal	Left	86 (843.66)	+4.6	3.74	5.01	-25.35
2	Normal	Left	85 (833.85)	+3.0	2.32	3.42	-32.16
3	Normal	Left	64 (627.84)	+5.8	1.21	2.31	-47.62
4	Varus	Left	84 (824.04)	-2.9	3.35	0.66	407.58
5	Varus	Left	56 (594.36)	-2.0	2.95	1.22	141.80
6	Varus	Right	94 (922.14)	-1.5	5.31	1.86	185.48

* + = valgus
\- = varus

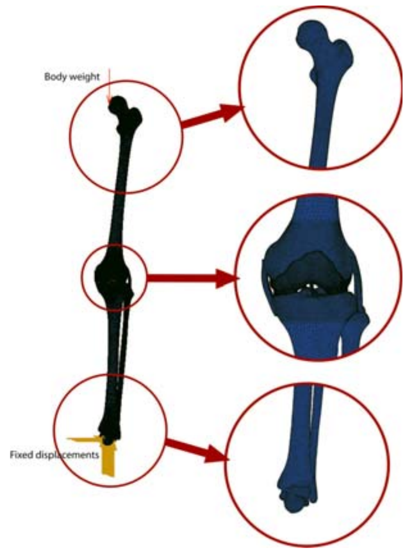

Fig. 4 An FE model with the boundary conditions

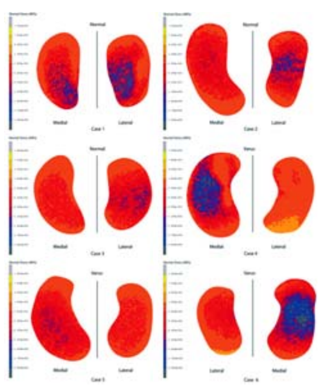

Fig. 5 The stress distributions on the articular cartilages

from 141.80% to 407.58% for the varus knee joints. The values of this parameter for normal knee joints, computed from the normal stresses reported in several studies[12,16,25], range from -10.87% to -44.00%. From the normal stresses reported by Fukuda et al[16], the value for a varus knee joint is 117.07%. It can be seen that the results from the previous literature have the same orders of magnitude, for both normal and varus knee joints, as the FE results obtained in this study.

Various computer-aided engineering (CAE) technologies are employed in this study to obtain the stress distributions in the normal and varus knee joints. The CT technology in conjunction with the employed image processing technologies allows the accurate geometric models of the domains to be created. With the proper boundary conditions and material assumptions, the results obtained from FEM are expected to be accurate. The process of creating an accurate geometric model of the domain of interest, which includes the determination of boundaries between different materials within the domain, is crucial to the accuracy of the obtained results. In the past, the technologies for this process were not available and, as a result, there was virtually no alternative to physical experiments when biomechanical problems were investigated. Nowadays, the modern CAE technologies have removed these obstacles and allowed numerical experiments to be performed instead of difficult physical experiments. This has subsequently allowed more questions in biomechanics to be explored and answered.

Conclusion

Finite element analysis shows that stress distributions in normal and varus knee joints are different. Varus knee joints have higher stresses in the medial compartments while normal knee joints have higher stresses in the lateral compartments. This pilot study demonstrates that FE studies are comparable to cadaveric studies. FEM can be used as an alternative method for studying and examining knee joints of patients.

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การศึกษาไฟไนต์เอลิเมนต์ของการกระจายหน่วยแรงในข้อเข่าปกติและข้อเข่าเสื่อม

ณัฐพล จันทร์พาณิชย์, พฤทธา ณ นคร, บัญชา ชื่นชูจิตต์, กฤษณ์ไกรพ์ สิทธิเสรีประทีป

วัตถุประสงค์: *เพื่อศึกษาการกระจายหน่วยแรงในข้อเข่าปกติและข้อเข่าเสื่อมโดยใช้วิธีไฟไนต์เอลิเมนต์*

วัสดุและวิธีการ: *การศึกษานี้พิจารณาข้อเข่าปกติและข้อเข่าเสื่อมอย่างละ 3 ตัวอย่าง ภาพถ่ายรังสีส่วนตัดอาศัยคอมพิวเตอร์ของขาถูกใช้เพื่อสร้างแบบจำลองเรขาคณิตสามมิติ ซึ่งประกอบด้วยกระดูก กระดูกอ่อนข้อเข่า หมอนรองกระดูกข้อเข่า และเอ็นข้อเข่า โดยแต่ละขาประกอบด้วย กระดูกต้นขา กระดูกหน้าแข้ง กระดูกน่อง และกระดูกข้อเท้า แบบจำลองเรขาคณิตสามมิติ แต่ละแบบจำลองจะถูกปรับไปสู่โครงแบบการยืนโดยอาศัยภาพถ่ายรังสี จากนั้นแบบจำลองไฟไนต์เอลิเมนต์สามมิติจะถูกสร้างจากแบบจำลองเรขาคณิตสามมิติที่ถูกปรับแล้ว ก่อนที่วิธีไฟไนต์เอลิเมนต์จะถูกนำมาใช้ เพื่อหาการกระจายหน่วยแรงบนกระดูกอ่อนข้อเข่าในการวิเคราะห์การเคลื่อนที่ของ posterior calcaneal articular surface ของกระดูกข้อเท้าจะถูกจำกัดในทุกองศาเสรี และน้ำหนักตัวจะถูกถ่ายลงในลักษณะของแรงกระทำแบบจุดที่หัวกระดูกต้นขา*

ผลการศึกษา: *ในข้อเข่าปกติหน่วยแรงตั้งฉากสูงสุดบนกระดูกอ่อนข้อเข่าใน lateral compartment จะสูงกว่าใน medial compartment เสมอในข้อเข่าเสื่อมแบบ varus ผลที่ได้จะตรงกันข้าม อย่างไรก็ตามในข้อเข่าปกติแต่ละข้อการกระจายหน่วยแรงที่เกิดขึ้นบนกระดูกอ่อนข้อเข่าทั้งสองด้านค่อนข้างจะสม่ำเสมอ ในทางตรงกันข้ามในข้อเข่าเสื่อมแบบ varus แต่ละข้อเมื่อเทียบกันแล้วจะพบหน่วยแรงตั้งฉากที่มีค่าสูงในพื้นที่กว้างบนกระดูกอ่อนข้อเข่าใน medial compartment*

สรุป: *ข้อเข่าเสื่อมแบบ varus จะมีหน่วยแรงตั้งฉากบนกระดูกอ่อนข้อเข่าใน medial compartment สูงกว่า ในขณะที่ข้อเข่าปกติจะมีหน่วยแรงตั้งฉากบนกระดูกอ่อนข้อเข่าใน lateral compartment สูงกว่า การศึกษาเบื้องต้นครั้งนี้แสดงให้เห็นว่าการศึกษาด้วยวิธีไฟไนต์เอลิเมนต์เทียบเท่ากับการศึกษาด้วยศพ วิธีไฟไนต์เอลิเมนต์สามารถถูกใช้เป็นวิธีทางเลือกในการศึกษาและตรวจข้อเข่าของคนไข้*