The Journal of Applied Science **Vol. 14 (No. 1): 9-14 [2015]**
วารสารวิทยาศาสตร์ประยุกต์
ISSN 1513-7805 Printed in Thailand

Research Article

A development of the finite element analysis for studying the osteoarthritis of the knee joint

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Abstract

The osteoarthritis means a knee joint disease which occurs frequently in aged woman especially the overweight person. More making physical activity is a cause that is able to activate the degeneration. The structure of deteriorated articular cartilage and meniscus will gradually changing until the knee joint that is not able to support the body weight. The mostly researches have investigated the stress on the different components of the knee joint. However, the study effect of the body weight on the knee joint degeneration with changing the posture has not been found. This study proposes the development of the finite element method in order to evaluate the stress on the meniscus of the knee joint with the varied flexion angles during changing the posture from sitting to standing. The osteoarthritis can be predicted by consideration of the determined transfer function. The simulation results found that the stress on the meniscus was increased with increasing external load. The maximum stress appeared on the medial meniscus and was significantly increased with the raising in the flexion angle.

Keywords: finite element analysis, stress distribution, meniscus, osteoarthritis, knee joint

Introduction

The knee joint is most important and the strongest joints in the human body. Many activities such as walking, running, sitting and standing essential based on movement of the knee joint. It provides the movement of the lower leg related to the thigh during supporting the body weight (Taylor, 2014). The most injury of the knee joint is well known as osteoarthritis (OA) or degenerative arthritis. Osteoarthritis causes degeneration of articular cartilage and meniscus, frequently experience in aged and obesity. While the body is moving, articular cartilage and meniscus produce the friction and wear and tear. Articular cartilage provides a smooth, low friction articulation and facilitates the transmission of loads to the underlying subchondral bone. The meniscus helps to distribute body weight. In case of obesity, knee joint is heavily loaded from the body weight. If he/she makes activity such as walking and running, causes more weight gain and more stress on the knee joint. Consequently, the meniscus is gradually declined and then it is not enable to support the overweight. In the older, the pain and degeneration in the knee joint has more than the younger. The injuries in the knee joint may be caused by flexion or extend the legs straight. In the first stage symptoms of the knee joint injury are not clear. Eventually, the structure of meniscus will be changed that affect daily life activities. Obviously, the patient undergo osteoarthritis has suffer both physical and mental. (Laopachee et al., 2015)

Many researchers have investigated the cause and problem of degenerative knee joint. Donahue et al. (2002) developed 3D FE model of the human knee joint, determined the effect of extent bony deformations on contact behavior and determined the constraining rotations other than flexion/extension affects the contact behavior of the joint during compressive loading. Peña et al. (2006) proposed 3D FE model of the healthy human knee joint including bones, menisci, articular cartilages and ligament under external load. Stress and strain are no uniform that occur in biological soft tissue. Zhang et al. (2009) constructed 3D FE model from CT images of a volunteer's knee joint. Applied load on double legs standing and flexion and then calculated and analyzed the pressure distribution of contact surfaces of knee joint. Chantarapanich et al. (2009) created 3D FE models from 3D geometric models to achieve stress distributions on the articular cartilages in normal and osteoarthritic knee joint. Normal knee joints have maximum stresses on the articular cartilages in the lateral compartments and the varus knee joints have maximum stresses in the medial compartment. Mohtajeb et al. (2012) proposed a 3D FE Model of the healthy human knee with fibula. Stress distribution on tibiofemoral joint (TF) without fibula was determined. When fibula was removed, almost all position on TF joint has maximum stress except the medial tibial cartilage. Dabiri et al. (2012) studied the effect of the articular cartilage on the knee joint mechanic using all knee joint components model. Moreover, it has been found that the fluid pressure distribute on superficial layer in the healthy more than the osteoarthritis. Stamenović et al. (2008) analyzed the design of the knee brace that is lightweight and inflatable (pneumatic). In clinical investigation, there are many cases are not able to examine or experiment in human body directly, finite element method (FEM) can be utilized for analysis the complex biomechanics. This paper proposes the preliminary study of the knee joint behavior using FEM, especially the meniscus during locomotive from sitting to standing. The knee joint model constructed composed of femur, tibia and meniscus. The external load of the varied flexion angles in the horizontal and vertical were determined in each body weight and applied on femur to evaluate maximum von-Mises stress on the meniscus. The transfer function is determined for prediction the osteoarthritis. The FE model was validated by comparing with other authors.

Materials and methods

Geometry of the knee joint

To complete the virtual model in this preliminary study, a geometrical model of the knee joint was finalized from native SolidWorks CAD3D. The 3-D model consists of three main compartments i.e. femur, tibia and meniscus without fibula which tibia is a major structure for support the body weight thus fibula was not considered in model developed. All of the components were simplified by combination articular cartilage with femur. An actual geometrical model is shown in Fig. 1(a). A virtual 3-D geometrical model of the knee joint at 0 degree and flexion angle are shown in Fig. 1(b) and (c), respectively. Each of the components was meshed as tetrahedral with mid side node by ANSYS. The contact type was defined to be no separation by assume that ligament and muscle exert in order to pull the bone connect together. Generally, mechanical properties of bones are varied with age, weight and gender, the model created are corresponding to Thai people. In this preliminary investigation purposes to understand the stress distribution and behavior of the knee joint in various conditions of the loading in z negative direction to understand body weight and stress on the meniscus when vary flexion angle using finite element method.

(a) (b) (c)

Fig.1 (a) An actual geometrical model and (b) A 3-D model of the knee joint and (c) Flexion angle of the knee joint

Boundary Conditions and Material Properties

This preliminary study, the maximum external load was determined and applied on the femur directly along z negative direction to evaluate stress of the knee joint in each body weight which distributed among areas via the nodes located on the femur. In this paper assumed that a human was standing, the load along z negative direction was transferred to femur. When human stands in double legs, the pressure of upper half body acting on single femoral head or force exerted in z negative direction was calculated from 62 percent of the body weight and divided by two (body weight $\times$ 62%)/2 (Zhang et al., 2009; Laopachee et al., 2015). The external load in each bodyweight varied with the 0-60 degree flexion angles was calculated as shown in Table 1.

Table 1. External load varied with flexion angles

Body Weight (kg)	Flexion Angle (Degree)							
	0		30		45		60	
	Horiz. (N)	Verti. (N)	Horiz. (N)	Verti. (N)	Horiz. (N)	Verti. (N)	Horiz. (N)	Verti. (N)
40	0	121	60	105	86	86	105	60
60	0	182	91	158	129	129	158	91
80	0	243	121	210	172	172	210	121
100	0	303	151	262	214	214	262	151
120	0	364	182	315	257	257	315	182

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The flexion angle in 90 degree was regardless because assumed that have not force on the bone. The simply support in z direction will be applied on the bottom of the tibia while body weight defined as external force was being applied on femur as shown in Fig. 2(a). The loading applied to flexion angle of the knee joint is separated into vertical and horizontal together by vector projection of loading as shown in Fig. 2(b). The coefficient of friction (COF) between the different components was assumed to be frictionless.

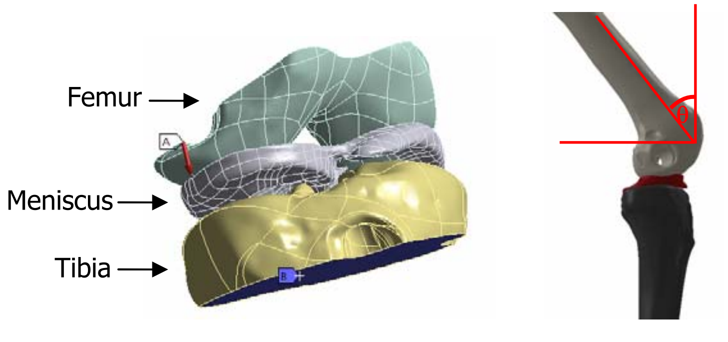

Fig.2 (a) External load applied on finite element model and (b) Vector projection of loading

As known material properties of bones are varied with age, weight and gender thus the model will be assumed to be linear isotropic material (Laopachee et al., 2015). Finite element analysis can be achieved using commercial software. In this study, material properties were introduced from the interesting paper as shown in Table 2.

Table 2. Material properties of finite element model of knee joint (Laopachee et al., 2015)

Components	Elastic Modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Femur	15	0.475	1000
Tibia	11000	0.3	1000
Meniscus	59	0.3	1000

Results and Discussion

The stress distribution always appears on meniscus, while the external load is being applied on femur directly. Table 3 shows stress distribution on a meniscus at 0 degree flexion angles under varied loads, the stress was increased with increasing external load. Stress distribution on meniscus against flexion angle at 0-60 degree under the 80 kg load and transfer function are shown in Fig. 3. Significantly, when the flexion angle of the knee joint was increased, the stress on the medial meniscus was increased. In contrast, the lateral meniscus was steady. The von-Mises stresses obtained were compared with that from the other author for the same analysis. As the result, the relationship between stress on meniscus and the flexion angle has trend corresponding to the other author but do not superimpose because the geometrical CAD model and contact area of the components before apply loading was different.

Table 3. Stress distribution on meniscus at 0 degree flexion angles under different loads

Body Weight (kg)	Load (N)	Stress (MPa)	
		Medial	Lateral
40	121	1.9	1.2
60	182	2.8	2.4
80	243	3.1	2.9
100	303	3.6	3.1
120	364	3.9	3.4

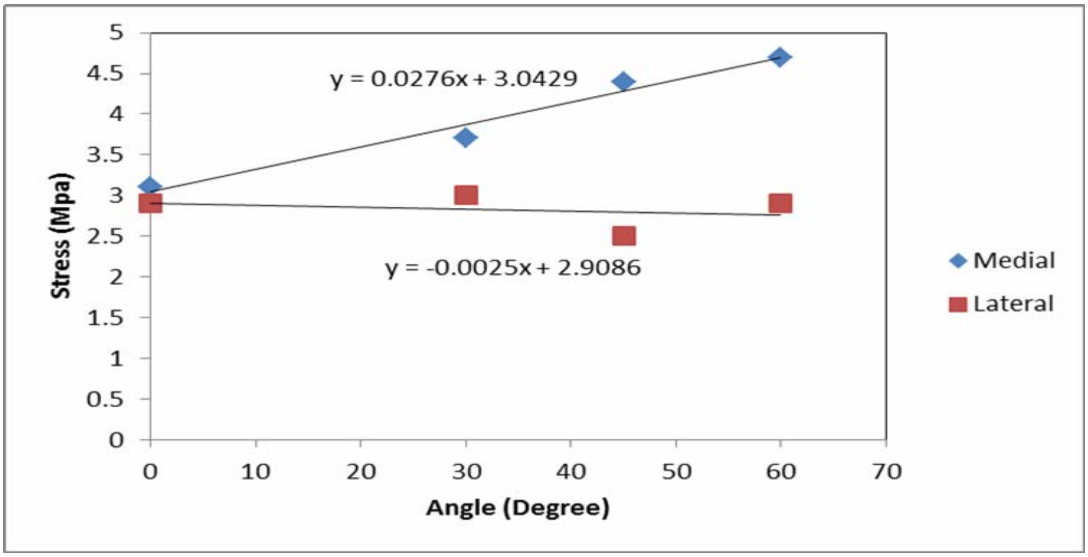

Fig 3. Stress distribution on meniscus against flexion angle at 0-60 degree under the 80 kg load

Conclusion

Osteoarthritis causes by the deformity of articular cartilage and meniscus, frequently experience in aged and obesity. Any bony components is compressed from load with long term, the risk of osteoarthritis is increased. In this investigation focused on stress distribution on meniscus that was varied with the external load and flexion angle. The simulation result showed that stress on the meniscus was increased with increasing body weight and external load. Furthermore, the stress occurred on medial meniscus was higher than the lateral meniscus and was significantly increased with raising flexion angle after applying 80 kg external load on the femur. Therefore, possibly the medial meniscus may be degenerated before others. However, the deformation of the knee joint while applying external loads that may depend on force exerted and flexion angle of the knee joint.

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