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NON-INVASIVELY ASSESSMENT OF KNEE CARTILAGE STRESS DISTRIBUTION USING MOTION CAPTURE SYSTEM AND FINITE ELEMENT METHOD

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Abstract. Knowing of the force of contact between the tibia and femur as well as the knee cartilage stress distribution is information which is of particular importance in clinical studies due to it is one of the basic indicators of cartilage state and also provides information of joint cartilage wear and predict when it is necessary to perform surgery on a patient. In this research, we applied various kinds of sensors such as a system of infrared cameras and reflective markers, three-axis accelerometer and dual-axis gyroscopes and foot pressure mat. The fluorescent marker and accelerometers are placed on patient hip, knee and ankle respectively. During normal walk we are recording space position of markers, acceleration and foot pressure distribution. Obtained data are including in biomechanics model of knee joint and geometry of this model is obtained from MRI slice images. This model includes the impact of ground reaction forces, tibia and femur contact force, patient body weight, ligaments and muscle force. When the model with boundary condition is created we apply the finite element method for non-invasively determine the cartilage stress distribution and its changes in real time.

1. Introduction

Everyday activities and daily routines such as walking, standing and recreation impose relatively large loads and movements on the human knee joint. This task can cause injuries and degenerations in the joint ligaments, menisci, cartilage and bone. Thus, knowledge of in vivo joint motion and loading during functional activities is needed to improve our understanding of knee joint degeneration and restoration. This value significantly depends of lot of factors like external loads, body weight, ligaments and muscles forces.

In the paper [1] the knee implants are used for directly measuring loads of subject during daily activities. In vivo knee measurements are very invasive and in the same case impossible. There are a lot of technique for measure an external variable which can be used in biomechanical and mathematically models.
Some studies are based on the registration of fluoroscopic images and computer model of knee [2]. Most recent method utilized force plate data, CT or MRI skeletal structure data and motion capture data obtained from an infrared position sensor [3],[4].

2. Mechanical model of knee

Knee joint motion is a complex combination of rotations and translations. The major parts involved in the knee kinematical behavior include femur, tibia, and patella. It has been shown a forces distributed in the knee joint in the Figure 1.

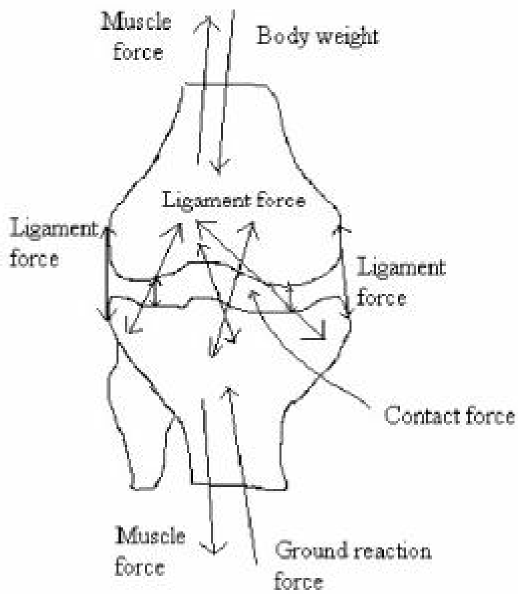

Figure 1. Forces on a knee joint

The main forces acting on knee joint are body weight and ground reaction force which are in the opposite direction. Very important in mechanics of knee are the ligament, muscles forces and contact force of tibia and femur. If there would not be these forces the knee joint cartilage would be flatted and probably there is no existing. The tibia force and moment will be in equilibrium when [5]:

$$F_r + F_b + F_{p1} \cdot N_1 + F_{p2} \cdot N_2 + \sum_{i=1}^{7} F_i = 0 \tag{1}$$

$$M_r + F_r \times P_r + F_b \times P_b + F_{p1} \cdot N_1 \times P_1 + F_{p2} \cdot N_2 \times P_2 + \sum_{i=1}^{7} F_i \times V_i = 0 \tag{2}$$

where F_r is the ground reaction force, F_b is the body weight, F_{p1} and F_{p2} are the two contact point forces, N_1 and N_2 are the two contact point normals, F (i =1..7) are the ligament and capsule forces, M_r is the knee joint driver moment along local z axis and P_r, P_b, P_1, P_2 and V (i =1..7) are the position vectors where the corresponding forces are applied. During presentation of this model we assuming that tibia and femur are rigid body, the deformation of this bone are very small opposite the cartilage and ligaments. The coefficient of friction between cartilage surfaces is very low due to existing of synovia fluid. The effects of ligament are ignored and it is supposed that muscule forces are superimposed and this sum is zero.

3. Experimental parts

In this study we used a commercial motion capture system OptiTrack. This system consists of six infrared cameras and four reflective markers. The markers are 1.5 cm in diameter and it's attached in various segment of the subject leg for unilateral gain analysis. The characteristic points are defined at great trochanter region, femoral lateral epycondile, at the tuberosity of the tibia and in the region of the center of the ankle joint.

Figure 2. Reflective markers position on the examinee leg

The computerized camera system captures the exact motion of these markers, which will identify the movement of the body while the volunteer walks in a straight line. The cameras are connected to a computer that collects gait cycle kinematical data. A 3D tracking software is then used to identify and convert 2D camera information into 3D motion data at different time frames. The result of motion tracking is a series of 3D coordinates for each numbered marker. To better understand kinematics and kinetics of gait we used and three-axial accelerometer. The accelerometer records acceleration in X, Y and Z direction with sample rate of 100 Hz. Each of these components represent sum of static acceleration defined by angle of inclination to corresponding axis and dynamics component stemming from movement during walk. The AMCUBE Foot Work pro system showen on Figure 3. is used for recording the ground reaction force.

Figure 3. Foot Work Pro system for foot pressure measurement

This system measure the foot pressure distribution during gate. This system consists of matrix of capacitor sensor dimension each one 7.6 x 7.6 mm. Range of measurement pressure is from 10 Kpa to 1200 Kpa. It is possible to calculate cumulative force during wade with integration pressure over contact surface. Sample rate of signal acquisition is 100 Hz. This platform is positioned on the pathway of gait and examinee across that by putting one leg on the sensors plate.

4. FE analysis

We take geometry of the finite element model from MRI slices for a specific examinee. Four reflective markers at the anatomical landmarks of the lower extremity are detected on MRI 3D reconstruction object.

For modeling of the cartilage and meniscus we implemented finite element formulation where the nodal variables are: displacements of solid, $\mathbf{u}$; fluid pressure, $\mathbf{p}$; Darcy's velocity, $\mathbf{q}$; and electrical potential, φ. A standard procedure of integration over the element volume is performed and the Gauss theorem is employed. An implicit time integration scheme is implemented, hence the condition that the balance equations are satisfied at the end of each time step is imposed.

More details of this parameter are given in [6]. Performing this system of equation using FEM and applying the boundary condition for tibia and femur we obtained stress distribution Figure 4. at the moment of the maximum reaction force value.

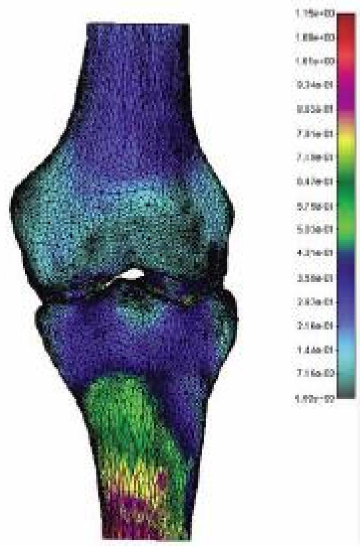

Figure 4. Stress distribution in MPa during gait at the moment of maximum reaction force val

5. Conclusion

Main goal of this study is noninvasive effective stress calculation for a specific given patient. Input data are provided from gait analysis experimental measurements and effective stress analysis is calculated from finite element analysis. It will open a new avenue for preoperative and postoperative surgical planning and treatment of the knee for specific patients.

There are also some limitations of the current study. We used material properties from literature data and it will be in future based on advanced image method for moving of the segments during MRI procedure. However, this study shows the ability of the current model to investigate the effect of different biomechanical factors on the stress at the knee joint. In this study we just used data obtained from infra red cameras and food pressure sensors. In the future work we try to replace an expensive system of infrared camera and markers with accelerometer and using acceleration data of leg segment in our calculation.

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