INFLUENCE OF MECHANICAL LOADING OF HIP JOINT DURING NORMAL GAIT

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Abstract: Osteoarthritis (OA) is a very serious hip joint disease, which is due to some of chemical, mechanical and genetic causes. One of OA frequent reasons is an excessive mechanical loading of articular cartilage. This paper specified contact stress and pressure distributions in the hip joint. Further, influence of changes in the loading modes and magnitudes on the contact pressure and stress distributions in the hip joint was evaluated. It appears that one of important factors influencing a rise and development OA of the hip joint is a magnitude and mode of loading. The hip joint loading during walking has a cyclic character. This loading mode is for the articular cartilage advantageous not only from the mechanical, but as well as from the nutrition, viewpoints. Articular cartilage is nourished with the synovial fluid which is "sucked in" at unloading and "driven out" at loading. When this physiological situation is disrupted by a change of loading mode, a continuous local overloading of the articular cartilage occurs resulting in its primary and permanent damage since its physiological nutrition can not proceed. The human organism tries to correct this adverse reaction by changes of its locomotion, but this causes further concentration of the mechanical loading into still smaller areas of the cartilage tissues, which results in a still more intensive overloading.

Introduction

Osteoarthritis (OA) is a very serious hip joint disease, which attacks mainly older population. OA causes a significant damage of human health connected with important social and economic problems. An OA prevention would contribute to early diagnoses and subsequent treatment of this disorder. It appears that one of important factors influencing a rise and development of OA in hip joint is a magnitude and mainly a mode of its loading. Geometrical shape and mainly a mode of loading cause different stress and contact pressure magnitude and distribution in the hip joint. This paper specified contact stress and pressure distributions in the hip joint. Further, influence of changes in the loading modes and magnitudes on the contact pressure and stress distributions in the hip joint was evaluated. The hip joint loading during walking has a cyclic character. This loading mode is for the articular cartilage advantageous not only from the mechanical, but as well as from the nutrition, viewpoints. Articular cartilage is nourished with the synovial fluid which is "sucked in" at unloading and "driven out" at loading. When this physiological situation is disrupted by a change of loading mode, a continuous local overloading of the articular cartilage occurs resulting in its primary and permanent damage since its physiological nutrition can not proceed The primary degenerative region (PDR) occurs with every patient at different femur head areas depending on a way of his/her locomotion. Most often (60%) OA is found on the top of the femur head. At the PDR location, an increase of the articular cartilage stress and strain concentration occurs influenced with the multiplied mechanical loading. Thus the cartilage is again overloaded and its secondary degeneration occurs resulting in a progressive expansion of the degenerative area. The human organism tries to correct this adverse reaction by changes of its locomotion, but this causes further concentration of the mechanical loading into still smaller areas of the cartilage tissues, which results in a still more intensive overloading. Such an always developed cycle: *overloading – change of locomotion – overloading* (OCO) is one of main factors influencing a rise and development of osteoarthritis of the hip joint. This paper deals with the stress and strain analyses of the hip joint, how it is influenced by the loading mode changes during human walk, and aimed at the assessment of significant factors of the OCO cycle described above. To carry out the stress and strain analyses of a 3D model of the hip joint, the finite element method (FEM) was applied.

Materials and Methods

The finite element model used in this study (Figure 1) represents a human hip joint. A 3D geometric model of the hip joint was based on a set of CT pictures. The whole model was meshed using the brick and shell elements in TrueGrid® and ABAQUS 651 programs. The model was solved as a nonlinear contact task, where the slide contact was defined between the femur cartilage and the pelvis cartilage. The model was solved by means of the ABAQUS 651 (Hibbit, Karlsson, Sorensen, Inc., Providence, RI).

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Ligaments were modelled by means of membrane elements. The ligament were treated as incompressible hyperelastic material where Neo-Hookean strain energy function is $\Psi = C_1 \cdot (I_1 - 3)$, where C_1=6 MPa.

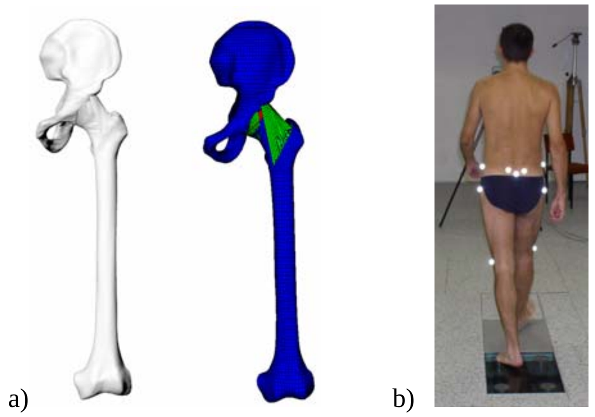

Figure 1: a) Geometrical and FE model of the hip joint (without connector elements), b) exp. measurements of the walking kinematics

The cartilage on the femur head and in the pelvis fossa was composed of transversely isotropic biphasic material (Table 1). At the location of a permanent overloading of the articular cartilage, a permanent damage was created. These degenerative changes in the cartilage were simulated by rising the modulus of elasticity E and, consequently, the elements were removed, which caused a location with an expressively higher stress concentration.

Table 1: Material properties of cartilage. E - Young's modulus, ν - Poisson's ratio, G - shear modulus, κ - permeability, γ - volume weight of the interstitial fluid, ϕ - solid volume fraction

E_1,E_2 [MPa]	**E_3 [MPa]**	**ν_{12} [-]**	**ν_{13} [-]**
5.8	0.46	0.1	0.0
G [MPa]	**κ x 10^{-7} [$mm.s^{-1}$]**	**γ x 10^{-6} [$N.mm^{-3}$]**	**ϕ [-]**
0.37	2.787	9.81	0.25

The femur and pelvis were meshed by the brick elements as deformable body. From the literature is known relation between Young's modulus E and density ρ of the bone tissue.

$$E = \begin{cases} 2003\rho^{1,56} & if \quad \rho \le 0,778\, g/cc \\ 2875\rho^{3} & if \quad \rho \ge 0,778\, g/cc \end{cases} \qquad (1)$$

A CT files typically contain data in Hounsfield Units. Relation between Hounsfield Units and density is

$$\rho = 4.8484 * 10^{-7} * HU + 5.1515 * 10^{-4} \qquad (2)$$

For all bone elements were estimated material properties in dependence on the bone density. Poisson's ratio was defined for all bone material as ν = 0.3.

Muscular groups were modelled by means of connector elements. This special element allows various definitions of the material properties, loading forces and the element behaviour. In general, the forces acting on the hip joint depend on the joint reactions as well as on the muscle forces. Thus to investigate the joint biomechanics, it is necessary to know for each motor task the force exerted by each muscle. The mechanical loading model was created by means of the muscular groups, all depending on the step phase. The magnitudes of the muscular group forces were taken over from the literature [1], [2]. The system mechanical loading was defined as a slow walk, when the femur was loaded by the loaded connector elements. All dynamic effects were neglected since a slow walk was assumed. The model was solved as a several static solution during gait cycle.

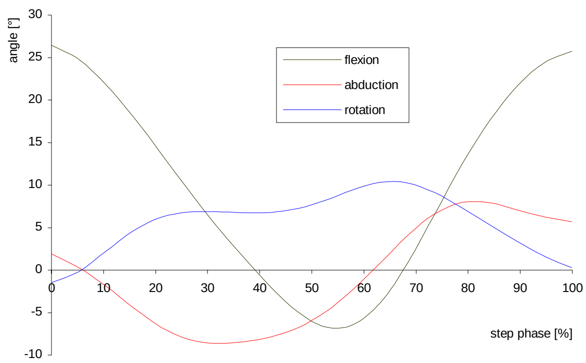

Figure 2: Kinematics of the hip joint

In this study the pelvis bone was assumed to be fixed. The displacements of the femur bone were applied to the reference node located at the centre of the lateral condyle. In Figure 2 the path of the displacements were shown. Kinematics of the femur and pelvis during normal walking were obtained from the experimental measurements (Figure 1).

Results

After carrying out several computation steps, a local permanent overloading place on the articular cartilage was identified. From the analysis results obtained it is evident that, due to changes in the hip joint "normal" loading, a local permanent overloading of the articular cartilage takes place. Then in this locality, after a subsequent artificial change of the tissue material properties, an abrupt growth of stress and strain concentration occurs. The contact pressure increase to $p_{max.}$ = 7.5 MPa. This trend is increasing together with increasing area of the damaged tissue. Further it is evident, that due to a consequent change in the model loading direction, the stress concentrates progressively repeatedly in the local areas of degenerative changes.

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After redistributing the mechanical loading in the hip joint, the stress and strain distributions tended to be more uniform and their values were reduced. The contact pressure decreased to $p_{max.}$ = 3.5 MPa.

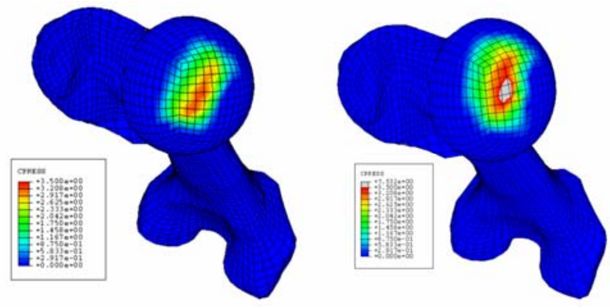

Figure 3: Comparison of the contact stresses exerted in the articular cartilage of both the physiologic (left) and arthritic (right) hip joints.

Conclusions

Based on the evaluation of the analyses results, a hypothesis, expressing that magnitudes and modes of mechanical loading directly influence the articular cartilage nutrition, can be suggested. Just a disruption of the cartilage physiological nutrition is one of factors influencing directly the onset and development of osteoarthritis in the hip joint. Still the analyses executed approximate a real situation in the hip joint. A mechanical loading model is an objective of future work, along with confirming a hypothesis according which the appropriate change of the human locomotion during gait could possibly reduce the OA development, which could be achieved by a special rehabilitation treatment. Next determinate a special physiotherapy treatment and create clinical trials on patients.

Acknowledgement

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