Application of the smoothed particle hydrodynamics method for the modelling of the ankle joint

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Abstract

This document is focused on the modelling of the ankle joint based on the smoothed particle hydrodynamics method (SPH). The material for the modelling of soft tissues, such as articular cartilage, based on the continuum approach is not sufficient. The hyperplastic material of the cartilage and synovial fluid is not represented well by the structure of the finite element. Under high loading, the large deformations or discontinuity inside synovial fluid or cartilage are created, which constitutes the limit for the finite element method (FEM). SPH is a meshless method, in which the material is represent by the particles for which the connectivity is determined by a neighbour list which is updated during calculation. The application of the SPH and FEM method for the modelling of the ankle joint under load gets very important information about the behaviour of the cartilages inside the joint.

Keywords: SPH, FEM, ankle joint, bone, cartilage, ligament, Smoothed Particle Hydrodynamics, Finite element, large deformation

1. Introduction

In this paper, a novel combination of continuum and discrete particle methods is applied for the modelling of large defection, damage and subsequent catastrophic failure in soft tissues. SPH is a meshfree Lagrangian method for the numerical solution of differential equations of motion [1]. The SPH method was created for the computational fluid dynamic analysis but since 1991, this method has been used in solid mechanics [2]. SPH method has been used to model the behaviour of soft tissues [3,4,5].

The analysis of energy distribution inside the joint under large loading is important in many applications such as sport, communication accidents and injuries to the bodies of soldiers during armed operations. To understand how the injuries are created, the model of the body must be similar to the physical tissues and their behaviours under load.

The aim of the study was to analyse the deformation process in the ankle joint during impact load. Two variants of the model were created. The first variant of the model consists of the joint modelled in continuum mechanics. The second variant of the model consists of cartilage and synovial fluid modelled by SPH inside the joint capsule.

2. Material and methods

Anatomically, the foot is one of the most complex structures with many joints and significant mobility. Figure 1 shows the model of the ankle joint which consist of three main bones: fibula(1), Tibia(2) and Talus(3). The bones are connected movable for dorsiflexion and plantarflexion of the foot. These components work together to provide the body balance and mobility and during axial load. Failure of one of these elements can lead to serious disturbances in the functioning of the entire limb while having a devastating impact on other segments of the body. The shape of the articular cartilage in the ankle was prepared from the MRI image data based on the distances between relevant bones. The geometry of a cartilage was validated based on the measurement data published by Millington [6]. The material properties for the bones were assumed such as in the work of Klekiel and Będziński [7]. The cartilage material is modelled as the nonlinear hyperelastic material represent by the Mooney-Rivlin model. Outside on the space of the cartilage component, the shell component was created to all ligaments representation. The shell component plays the role of the articular capsule and is a geometric restriction for particles.

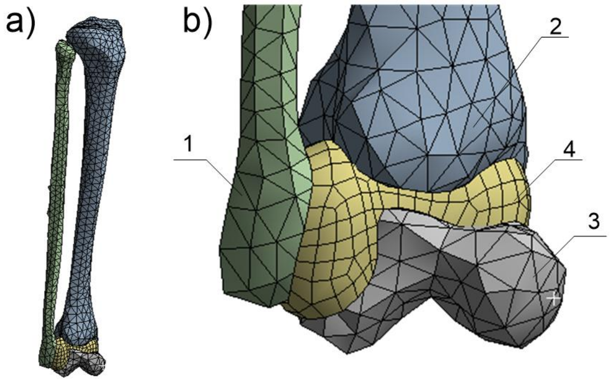

Figure 1: Ankle joint model: a) view of the whole model, b) details about the ankle joint: 1- Fibula, 2-Tibia, 3-Talus, 4-articular joint with cartilage, synovial fluid and articular capsule

The model was loaded by the initial velocity for the Talus and the rotary movement of the talus corresponding to the dorsiflexion of the foot. From above, the proximal head of the Tibia was loaded by the mass of the leg.

3. Result and discussion

The material properties of the articular cartilage model represented by the particle (Figure 2) were identified based on the Mooney-Rivlin model of material for which the coefficients

ACKNOWLEDGMENTS: This investigation was supported by a research grant, as a part of the project DOBR-BIO/22/13149/2013 financed by NCBiR.

were designed by Butz [8]. The model of the ankle joint was acting by the velocity directed vertically along the main biomechanical axis of the leg. Talus bone is rotated performing movement in the same way as during dorsiflexion of the foot, which is typical for large loading [9]. Those complicated initial conditions lead large shear stresses in the distal tibia head for continuum model. Using the SPH method, these stresses are smaller for the same load conditions.

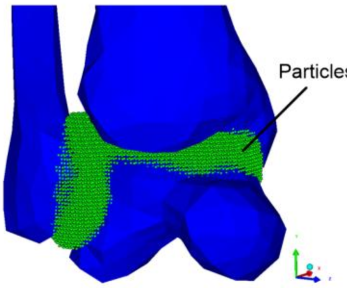

Figure 2: Particles representing the articular cartilage and synovial fluid inside the joint capsule

The figure 3 presents the graph for maximal stresses for two variants of the model. The maximum value of the stress in the Tibia for continuum model is higher than for the model with SPH method.

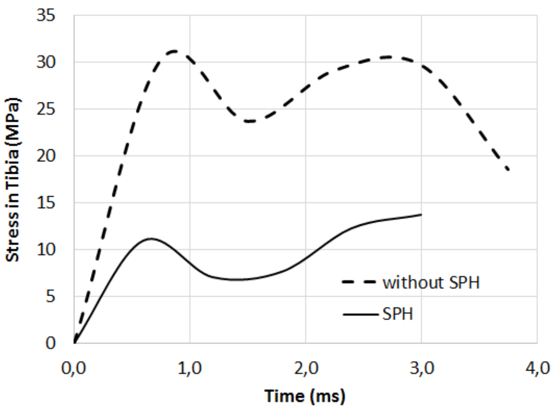

Figure 3: The von Mises stress distribution for the Tibia

The energy inside Tibia for both models are also different. The total energy for the model with SPH is about 1J but for the continuum model, it is about 3J. The results suggested that the model based on the particles reflects the damping property of the joint.

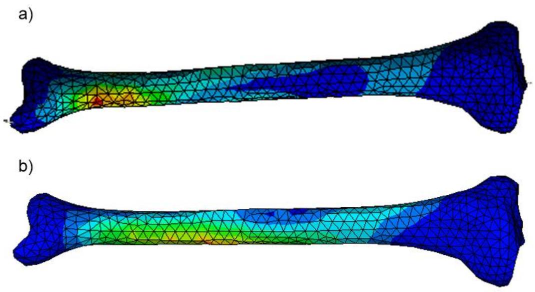

Figure 3: Stress distribution for the Tibia in time 3ms for a) continuum mechanics and b) the model with SPH

Based on these results, it can be stated that the joint modelled using SPH gets more information about efforts in the ankle joint during high loading and movements between bones. The pressure inside the capsule is increase but the resistance of the motion does not change.

4. Summary

Our investigation was focused on the comparison between the continuum and particle approach to the modelling of the processes in the ankle joint during high loading. Application of the SPH method was useful for modelling motion between bones in the joint. Usually, the dynamic friction coefficient for healthy joint is about 0.01-0.05. During large loading, the cartilage deformation is also large, which leads to the stress increase as a result of resistance to the movement in the joint. Based on the SPH approach, the material of cartilages and synovial fluid provides the possibility of large deflection such as for hyperplastic materials but at the same time, the movement in the ankle is undisturbed.

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