

THE EFFECT OF PERMEABILITY OF CARTILAGE SUPERFICIAL ZONE ON THE BEHAVIOR OF STRESS RELAXATION AND CREEP OF HUMAN ANKLE JOINT

Lu Wan^{*†}; Guoan Li^{*}

^{*}Bioengineering Lab, Massachusetts General Hospital/Harvard Medical School, Boston, MA

[†]Department of Physics, Massachusetts Institute of Technology, Cambridge, MA

Lu Wan, 55 Fruit Street, GRJ 1215, Boston, MA 02115, Tel: 617-726-1346, Fax: 617-724-4392, Email: lwan@partners.org

INTRODUCTION

The microstructure of articular cartilage could be divided into four distinct zones: the superficial zone, middle zone, deep zone, and calcified cartilage zone. It is believed that the superficial zone of articular cartilage has a lower permeability, which may be related to the close packing of the collagen fibrils resulting in a system of much narrow channels which offer a greater resistance to flow [1]. This parametric study investigated the influence of permeability of the superficial zone on the behavior of cartilage stress relaxation and creep of human ankle joint using a 2D biphasic poroelastic finite element model (FEM) that was created from a living human ankle joint.

METHODS

The 2D geometry of the tibial cartilage and talar cartilage layers was digitized from a MR image of a living subject's ankle joint and then imported into ABAQUS finite element software (ABAQUS, Inc., Providence, RI) to create a plane-strain mesh model. The top 0.1mm of the cartilage was defined as the superficial zone [2]. The articular cartilage was modeled as being attached to a cortical bone of approximate 6 mm thickness. Elastic material properties were used for the bone with Young's modulus as 2GPa and Poisson's ratio as 0.2 [3]. Poroelastic material properties were used for the superficial zone and the other zones of the cartilage. The articular surface was assumed perfectly permeable. The Young's modulus and the Poisson's ratio were $E=0.4667$ MPa and $\nu = 0.1667$ throughout the cartilage. The permeability of the cartilage except the superficial zone was $k = 7.5 \times 10^{-15} \text{ m}^4 / \text{N} \cdot \text{s}$ [4]. The permeability k' of the cartilage surface layer was assigned to be 0.2k, 0.4k, 0.6k, 0.8k and k, respectively. The cartilage contact was assumed to be frictionless. The bottom of the talus cortical bone was fixed all the time for all the cases.

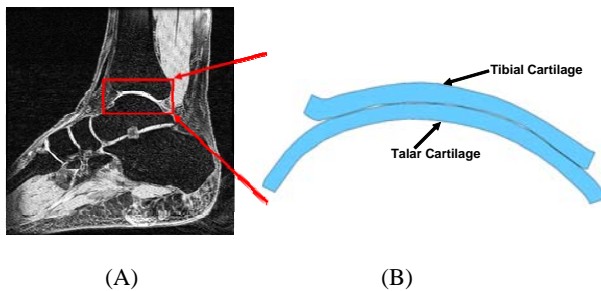


Fig.1 (A) MR image of the ankle joint; (B) cartilage model of the ankle joint created from (A).

1. Stress Relaxation

A total vertical displacement of 0.15 mm (corresponding to an approximate 5% compression ratio) was completed on the top of tibia within a ramp time $t_0=1$ s. The tibia was kept in equilibrium for a further 500s. The reaction force on the contact surface was predicted as a function of time.

2. Creep

A vertical 5N/mm load was evenly applied to the top of tibia within a ramp time $t_0=1$ s. The load was kept constant for 500s.

The displacement of the tibia was predicted as a function of time.

RESULTS

1. Stress Relaxation

The peak reaction force (at time $t_0=1$ s) were 6.08, 5.85, 5.63, 5.45, 5.28N/mm for $k'=0.2k$, 0.4k, 0.6k, 0.8k and k, respectively (Fig. 2(A)). The reaction force increased monotonically while the surface layer permeability decreased. When the surface layer permeability was reduced to 20% of the cartilage permeability, the reaction force increased by 62% at 50s relaxation.

2. Creep

The tibia displacement at time $t_0=1$ s were 0.179, 0.183, 0.187, 0.190, 0.194mm for $k'=0.2k$, 0.4k, 0.6k, 0.8k and k, respectively (Fig. 2(B)). The displacement decreased monotonically while the surface layer permeability decreased. When the surface layer permeability was reduced to 20% of the cartilage permeability, the tibia creep displacement decreased by 8% at time $t=51$ s.

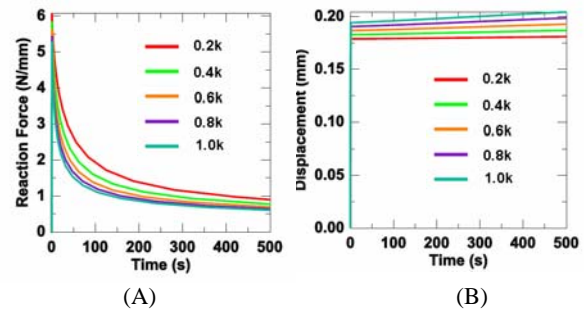


Fig. 2 (A) reaction force curves for different surface layer permeability during stress relaxation; (B) displacement curves for different surface layer permeability during creep.

DISCUSSION

Although it is well known that articular cartilage is a heterogeneous material due to its microstructure, people usually simplify it as a homogeneous material with uniform permeability throughout the cartilage layers for finite element analysis of anatomic joint contact problems [3, 5]. This study showed that the variation of the permeability of the surface cartilage layer could cause significant differences of the joint contact problems, such as stress relaxation and creep. Further experimental investigation of the permeability variation in the intact joints might be helpful to facilitate the finite element analysis of joint contact problems. In the future, a 3D FEM calculation will be performed to investigate the effect of permeability change of cartilage superficial zone on the joint contact deformation.

REFERENCES

1. Maroudas et al. *Nature*, 1968;
2. Fetter et al. *J Orthop Res*, 2006;
3. Han et al. *J Biomech*, 2005;
4. Spilker et al. *Computational Methods in Bioengineering*, 1988;
5. Donzelli et al. *J Biomech*, 2004