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A functional effect of the superficial mechanical properties of articular cartilage as a load bearing system in a sliding condition

N. Sakai[a,c,*], C. Hashimoto[a], S. Yarimitsu[b], Y. Sawae[a,c], M. Komori[a], T. Murakami[c]

[a]Integrated System Engineering, Kyushu Institute of Technology, Kitakyushu, Japan
[b]Intelligent Mechanical Systems, System Design, Tokyo Metropolitan University, Tokyo, Japan
[c]Research Center for Advanced Biomechanics, Kyushu University, Fukuoka, Japan

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Abstract

The structure and composition of articular cartilage show depth-wise inhomogeneity and anisotropy. In particular, the dense collagen network covers and reinforces the superficial tangential zone of the tissue. It is thought that this peculiar structure offers the excellent tribological property of articular cartilage. The purpose of this study was to investigate the functionality of the superficial tangential zone (STZ) of articular cartilage as a load bearing system. The 2-dimensional finite element (FE) model was accepted for sliding configuration with sufficient extent of sliding distance. The standard model as a control was carried from our previous study, which included depth-dependent Young's modulus of the solid phase, fiber reinforcement with strain-dependency and permeability with compaction effect. The mechanical property of the superficial layer was modified for a parametric study of its functionality. According to research results in the past, the tangential stiffness of the fiber reinforcement of the STZ model was enhanced, and the following anisotropic permeability was also modified. The stationary contact condition and the migrating contact condition were examined to compare the effect of the superficial tangential layer. The result showed that the significant reduction of friction coefficient was found in migrating contact condition of the STZ model. In the observation of field output of FE analysis, the contacting surface formed a thin low permeability layer, which would enable the high fluid pressure and the low fluid flow at the same time. It seemed that the stiffening of the fiber reinforcement of the superficial layer promoted the formation of the low permeability layer. Beyond the effectivity of the fiber reinforcement of biphasic matrix on the interstitial fluid pressurization, the findings of this study indicated that the compaction effect on the permeability would involve a quite complex phenomenon in long term migrating contact sliding.

Keywords: Articular cartilage; Biphasic lubrication; Load bearing; Material property; Anisotropy; Inhomogeneity

1. Introduction

Articular cartilage plays an important role to maintain very low friction in wide operating ranges. The study on the mechanics of the cartilaginous tissue is usefully applicable to a medical insight of the synovial joint diseases, cultivating conditions for regenerative medicine and an engineering feature of a load bearing system such as artificial cartilage. The cartilaginous tissue contains high water fraction as a fluid phase. Proteoglycan matrix is enmeshed in type II collagen fibril network, which mainly resists the tensile load. The cartilaginous tissue is commonly divided into 3 characteristic layers, whose are called superficial, middle and deep zone. In the superficial zone, the constitution of collagen fibril network is dense and predominantly oriented to parallel with tissue surface [1–3]. Articular cartilage shows compressive strain inhomogeneity and anisotropy from the surface to deep zone [4–7]. The tensile stiffness of cartilaginous tissue is experimentally much higher than the compressive stiffness in equilibrium condition [8], and mechanical behavior of articular cartilage tissue exhibits tension–compression nonlinearity [9].

*Corresponding author at: Integrated System Engineering, Kyushu Institute of Technology, Kitakyushu, Japan. Tel./fax: +81 93 884 3574.
E-mail address: sakai.nobuo@ise.kyutech.ac.jp (N. Sakai).
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Articular cartilage realizes excellent frictional property by the synergistic cooperation of several frictional modes, called as "adaptive multimode lubrication" [10]. At low sliding speed, several boundary lubrication mechanisms considerably enhance the tribological property [11–19]. Articular cartilage shows the time-dependent compressive behavior, which was well explained by "biphasic model" [20]. The further biphasic complex of articular cartilage on frictional behavior has been expanded as "biphasic lubrication mechanism" [21]. When an impermeable counter surface contacts to the biphasic material, the interstitial fluid is trapped and pressurized within the apparent contact area. While the fluid starts flowing along the gradient of the pressure, the pressurized interstitial fluid also presses the solid phase, which is well reinforced in the tensile direction by the collagen network. This situation causes high fluid pressurization in the contact area and the consequent reduction of the solid-to-solid contact load. The high fluid load support results in low friction coefficient under an assumption of a nonviscous property of the fluid [22]. As the fluid load pressurization was observed in unconfined compression [23], the reduction of friction coefficient was experimentally proved by the correlation between the direct measurement of the contact fluid pressure and friction coefficient [24].

It is said that excessive loading cycles increase the possibility of the disruption of the collagen–proteoglycan construction [25]. The repeated compressive load of in-vitro study caused the reduction of tensile strength prior to the obvious surface damage [26]. In addition to the mechanical weakening, the fragments of collagen II and glycosaminoglycans were released to culture medium [27]. Semi-impact loading test also showed superficial disruption with textual alteration, whereas the deeper zone remained undamaged [28]. An anatomical observation following an indentation test showed the structure-related deformation associated with the superficial tangential zone [29]. The removal of the superficial zone completely changed the typical deformation field of the indentation test [30,31]. Once a splitting of the cartilage surface occurs eventually, the surface lesion develops into full thickness of the cartilaginous tissue with surface roughening and fibrillation. The surface structure with the fiber reinforcement is thought to be an important factor for the functionalities of articular cartilage.

A computational model indicated that the experimental indentation well correlated with the stiffness of superficial layer [32]. The tensile stiffness of the thin specimen including superficial layer was about 6 times higher than that prepared from the middle layer [33]. Because of the difficulties of the experimental testing, prescribed FE model and curve fitting method were utilized to estimate the material properties including the inhomogeneity and the anisotropy. The orientation and the density of collagen network for FE model were determined by microstructural insights [34,35], and verified by quantitative optical analysis [36]. In addition to the material testing, the depth-dependent inhomogeneity enhanced the ratio of the interstitial fluid support in spherical indentation [37].

Anisotropy of fluid transport was evaluated in the past by diffusional anisotropy using fluorescence recovery after photobleaching (FRAP). In the superficial layer, macromolecular diffusion showed significant anisotropic property in particularly the compressed condition [38], in which the diffusion rate in the fiber direction was larger than perpendicular direction. On the other hand, the curve fitting estimation in compressed condition showed a significant decrease of the permeability perpendicular to the compression [39]. Since the anisotropy of the permeability was thought to derive from an intrinsic structural mechanism of the fiber arrangement, the depth-dependent anisotropy of the permeability was estimated by the curve fitting method of FE analysis using the prescribed distribution of the density and the orientation of collagen fiber network [40].

A knee model with the depth-dependent anisotropy enhanced the fluid load support in a loading condition [41]. Beyond the loading analysis, the migrating sliding configuration as a start-up friction was examined to confirm the effect of anisotropic low tangential permeability in the superficial layer [42], which resulted in a reduction of friction coefficient. For the biphasic lubrication mechanism, the tensile reinforcement of the tissue by the collagen network plays a crucial role to enhance the interstitial fluid pressurization and for following superior frictional property. The superficial tangential layer is reinforced with the dense collagen network This structure is interesting from not only a physiological viewpoint but also an engineering viewpoint as a load bearing system. In the present study, we focused on the effect of anisotropic fiber reinforcement in the superficial tangential zone, which also involved anisotropic permeability property. The transitional friction coefficient in sliding condition was examined using biphasic FE analysis. The result showed that a peculiar decrease of friction coefficient was observed in migrating contact condition.

2. Materials and method

In this study, we firstly prepared a standard biphasic FE model as a control model. Although the material properties of the standard model were carried from our previous paper [43], we summarize the composition of the standard model according to the purpose of this study. Then, the material properties of the superficial tangential layer of the standard model were altered to assess the effect of anisotropic material properties from an engineering viewpoint. The effect of the anisotropic superficial layer was evaluated by 2 sliding conditions, which were the cylindrical cartilage sliding on a plate and the cylindrical indenter sliding on the cartilage. The latter sliding condition was the migrating contact condition as a dynamic condition, which was introduced in the papers past [44,45]. Several parametric studies beyond the biological condition were also conducted for confirming the effect and further applications.

2.1. The constitution of the standard model

A commercial package for FE analysis (ABAQUS Ver.6.8-4) was used in this study. The 2-dimentional modeling was