A THEORETICAL STUDY OF THE MECHANICAL RESPONSE OF ARTICULAR CARTILAGE TO IMPACT LOADING

LePing Li * and **Walter Herzog**

Human Performance Lab, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada

INTRODUCTION

Experimentally, the stresses of articular cartilage have been found to depend on the loading rate [1,2]. Theoretically, the short-term transient behavior of cartilage in unconfined compression has been explored at strain rates of 0.01, 0.1 and 1%/s using a poroviscoelastic model [3]. In the present work, the transient stress-strain relationship, the dependence of stiffness on tissue volume change, and the load sharing between the solid matrix and fluid pressurization were explored in the full range of strain rates (0-∞), in an attempt to explain the nonlinear behavior of cartilage in an unconfined geometry under impact loading.

METHODS

Articular cartilage was considered as a fluid-saturated, nonfibrillar matrix reinforced by a collagen fibrillar matrix [4]. The elastic response was obtained analytically for large deformations. Letting the fibrillar modulus be $E_f^0 + E_f^\varepsilon \varepsilon_r$, the fluid pressure and the total axial stress (Cauchy) for instantaneous axial compression in an unconfined geometry are, respectively,

$$p_f = \left(E_f^0 + E_f^\varepsilon + 2\mu\right)\left(e^{\varepsilon_r} - 1\right) - E_f^\varepsilon \varepsilon_r \tag{1}$$

and

$$\sigma_z = 2\mu\left(e^{\varepsilon_z} - e^{\varepsilon_r}\right) - \left(E_f^0 + E_f^\varepsilon\right)\left(e^{\varepsilon_r} - 1\right) + E_f^\varepsilon \varepsilon_r \tag{2}$$

where μ is a Lamé constant of the nonfibrillar matrix. The finite element method was used to obtain solutions for strain rates from zero to infinity. The standard porous element in ABAQUS was adopted for the nonfibrillar matrix containing fluid. A user-defined continuum element was introduced for the fibrillar matrix to replace the spring elements used previously, in order to eliminate deformation incompatibility between the discrete matrices.

The Young's modulus and Poisson's ratio of the nonfibrillar matrix were 0.36MPa and 0.38 respectively; the fibrillar modulus was (3+1600ε_r)MPa; and the tissue permeability was 0.003 exp(10×dilatation) mm^4/Ns. These material properties were chosen in a previous study [5] based on values reported and data fitting.

RESULTS AND DISCUSSION

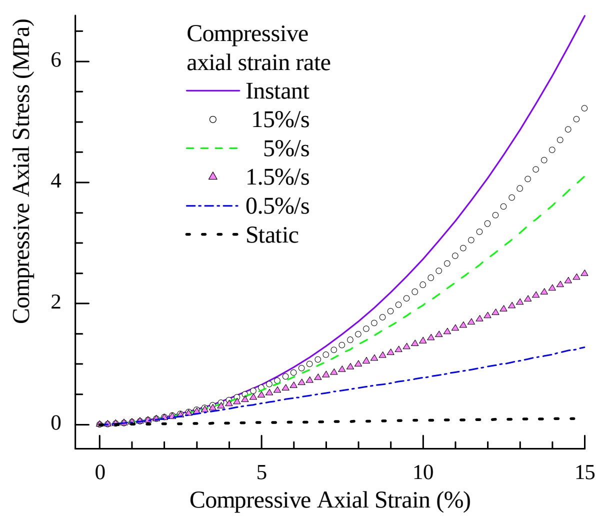

Fig. 1

The static stress-strain relationship was almost linear, while the transient relationship for high strain rates was highly nonlinear (Fig.1). The stress-strain patterns for unconfined compression (Figs.1 & 2) were similar to those observed in indentation tests [2], but the predicted stress was lower than the measured. The differences in magnitude may have been caused by the differences in material properties, boundary conditions and geometry. The results suggest that high speed impact testing may not always be necessary for approaching the instantaneous stress or stiffness. At 5% axial strain, a compression at 15%/s produced a response very similar to that seen for an instantaneous compression; at 10% axial strain, the same compression rate (15%/s) still produced a stress that was close to the instantaneous stress (Fig.2). The larger the strain, the higher the strain rate required to approximate the instantaneous response.

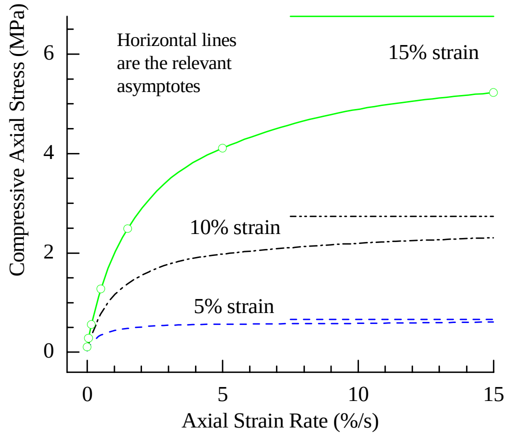

Fig. 2

The strain rate dependence of fluid pressurization is shown with the ratio of load acting on the fluid over the total axial loading (the solid line in Fig.3). The results generally agree with experimental observations (e.g. [6]). The contribution to load bearing by the fluid pressure increased quickly with strain rates: at a low strain rate of 0.05%/s, fluid pressurization supported about 60% of the load (Fig.3). The solid matrix carried 100% of the load at equilibrium. With increasing strain rate, the load born by the solid decreased gradually to about 50% of the static load when the strain rate increased to infinity (the dashed line in Fig.3). These observations indicate the predominant contribution of fluid pressurization, which is associated with fibril reinforcement (e.g. equation (1)), in the transient response of articular cartilage to high speed compression.

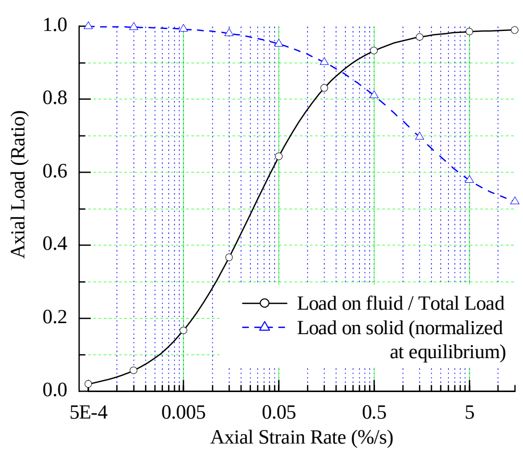

Fig. 3

The apparent stiffness of cartilage under impact loading was several times greater than that under static loading. For a given axial strain (a solid line in Fig.4), a higher strain rate was associated with a stiffer tissue. Stiffness also increased monotonically with strain rate for a given volume change (Fig.4). For a strain rate ≥ 0.5%/s, a greater volume change produced higher tissue stiffness. However, when the axial strain was given (solid lines in Fig.4), a greater volume change resulted in lower tissue stiffness, because an increase in volume change was then associated with a decrease in strain rate. Consequently, changes in tissue volume are not good indicators of the transient stiffness of articular cartilage. The fibrillar strain, or fibrillar modulus, is a better indicator of the stiffness.

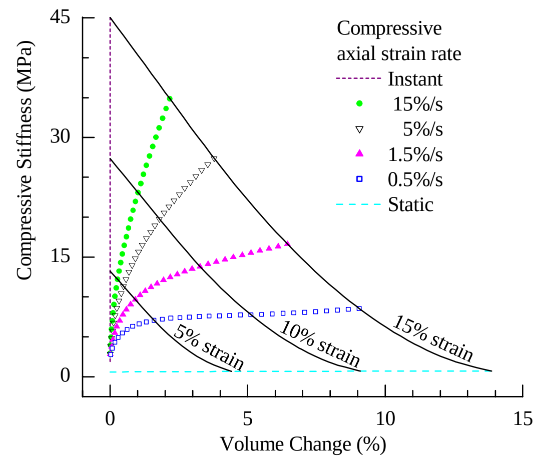

Fig. 4

The effect of strain rate on cartilage response has been investigated previously using a poroviscoelastic model [3]. It was concluded that the short-term viscoelastic behavior of articular cartilage, subjected to a fast ramp strain rate, was primarily governed by a fluid flow-independent viscoelastic mechanism. Since the fastest strain rate investigated in that study was 1%/s [3], it is not clear whether the conclusion can be extended to greater strain rates. The results of the present work emphasize the strain (0~15%) and strain-rate (0~∞) dependence of the short-term response in unconfined compression using a mechanism of fluid-driven fibril reinforcement. Fibrillar viscoelasticity, however, may play an additional role in the mechanical response of articular cartilage in compression.

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* Corresponding author. Email: leping@kin.ucalgary.ca