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Research Paper

Intrinsic viscoelasticity increases temperature in knee cartilage under physiological loading

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ABSTRACT

Metabolism of proteoglycans and hyaluronic acid has been shown to be temperature-dependent in cartilage explants, with optimal anabolic effects between 36 °C and 38 °C. At rest, the temperature of human knee has a value of around 33 °C. We aim to show in this study that viscoelastic properties of healthy human cartilage allow its temperature to reach those optimal temperatures during physiological mechanical loadings. We developed a model allowing to determine the temperature increase in cartilage due to viscous dissipation. The model had three parameters, which were determined experimentally. The first parameter was the energy dissipated by cartilage samples submitted to cyclic stimulation. It was obtained with standard in vitro mechanical testing. The second parameter was the cartilage heat capacity and was measured in vitro with differential scanning calorimetry. Finally, the third parameter was the time constant of cartilage heat transfer and was obtained with in vivo magnetic resonance thermometry performed on four volunteers. With these experimentally determined parameters, the model predicted that cartilage dissipation is sufficient to raise the temperature in healthy knee cartilage from 33 °C to 36.7 °C after a 1 h walking. These results showed that intrinsic viscoelastic properties of the cartilage could induce a temperature increase optimal for the production of proteoglycans and hyaluronic acid. Interestingly, degenerated cartilage did not present high enough viscoelastic properties to significantly induce a temperature increase. Taken together, these data suggest an association between cartilage dissipation and its homeostasis.

1. Introduction

Temperature is a fundamental quantity in mechanics. However, most of the works performed in biomechanics considers the studied processes as isothermal due to the fact that mammalians have a regulated system for maintaining their temperature constant (Romanovsky, 2007). The isothermal hypothesis may be locally wrong when considering viscoelastic tissues submitted to dynamic loading. Indeed, viscoelastic materials dissipate part of the mechanical energy into heat, creating thus an internal heat source in the materials (Ratner and Korobov, 1966). The corresponding effect may be

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spectacular, as it has been shown that an increase in temperature of 6.5 °C can be generated between the outer and inner parts of a horse tendon during intense running (Wilson and Goodship, 1994). The avascular region of the tendon was the site of the most marked temperature increase. This observation suggests that the key point to obtain an increase in temperature in a tissue is an insufficient blood supply to transport the generated heat.

Given that articular knee cartilage is avascular (Oldershaw, 2012) and has viscoelastic properties (Hayes and Mockros, 1971; Huang et al., 2003), a local temperature increase in the cartilage could then be obtained due to dissipation following a cyclic mechanical loading. This is especially interesting since it has been shown that increasing temperature affects the metabolism of cells. Indeed, the rate of proteoglycan synthesis and the release of newly synthesized proteoglycans by chondrocytes are increased in cultures at 37 °C compared to 32 °C (Brand et al., 1991). Likewise, for the same temperature increase the rates of hyaluronic acid synthesis and glycolysis are also enhanced (Castor and Yaron, 1976).

The knee temperature at rest has a value of around 33 °C in healthy human subjects (Becher et al., 2008; Harris and McCroskery, 1974). A temperature close to 37 °C due to dissipation subsequent to a mechanical loading would enhance the metabolism of chondrocytes.

In this study, we aim to verify if cartilage dissipation under mechanical loading is sufficient to raise temperature from 33 °C to temperatures close to 37 °C, at which proteoglycan and hyaluronic acid metabolisms are optimal. As well, we aim to evaluate if a degeneration of cartilage will also affect temperature increase, since mechanical dissipation is dependent to the matrix microstructure and composition.

2. Material and methods

2.1. Experimental design

In order to determine the temperature increase in cartilage under mechanical loading due to its intrinsic viscoelastic properties, a mathematical model was developed. The model encompassed three parameters determined experimentally (Fig. 1). The first parameter was the power of energy dissipated subsequent to a mechanical loading, which was quantified in vitro on human cartilage samples. The second parameter was the cartilage heat capacity, which was measured in vitro on human cartilage samples with differential scanning calorimetry. Finally, the third parameter was the time constant of cartilage heat transfer. This time constant was determined on four volunteers by magnetic resonance thermometry.

As viscoelastic properties are related to material microstructure (Shaw and MacKnight, 2005), we quantified the energy dissipation of human cartilage samples taken from different sites of the femoral heat of subjects who underwent hip arthroplasty. We defined each sample as "healthy" or "degenerated" depending on their dynamic stiffness. Indeed, it has been shown that in osteoarthritic cartilage dynamic stiffness is 70% lower than in healthy cartilage (Knecht et al., 2006). The influence of cartilage degeneration on temperature increase was then assessed.

2.2. Mathematical model

The model that determined temperature evolution in a material under mechanical loading is derived from the heat equation (Dinzart et al., 2008)

$$mc\frac{\partial T(x,t)}{\partial t} = k\nabla^2 T(x,t) + \dot{Q} \tag{1}$$

where in our particular case, m is the cartilage mass, c its heat capacity, k its conductivity and $\dot{Q}$ its energy dissipation when subject to cyclic loading.

As our cartilage samples are thin, the temperature distribution in the system can be assumed as quasi-uniform (Dinzart et al., 2008). Therefore Eq. (1) is reduced to

$$mc\frac{dT(t)}{dt} + \lambda S(T(t) - T_0) = \dot{Q} \tag{2}$$

where $k\nabla^2 T(x,t)$ is simplified to $\lambda S(T(t)-T_0)$ when averaged over the cartilage thickness. The heat flux represents the heat transfer out of the cartilage surface S. λ is the heat transfer coefficient at the system frontier and T_0 the temperature outside the system, which value is 33 °C, corresponding to knee joint temperature at rest (Harris and McCroskery, 1974).

Cartilage dissipation is determined by hysteresis stress–strain curve (Szarko et al., 2010)

$$\dot{Q} = Hf \tag{3}$$

where H is the area enclosed by cartilage hysteresis curve and f the loading frequency.

Combining Eqs. (2) and (3) the temperature evolution becomes

$$mc\frac{dT(t)}{dt} = Hf - \lambda S(T(t) - T_0) \tag{4}$$

Eq. (4) can be rewritten as

$$\begin{cases} \dot{T} + aT = b \\ T(t_o) = T_i \end{cases} \tag{5}$$

Identifying the constants a and b with the parameters of Eq. (4), the analytical solution of Eq. (5) is then given by

$$\begin{cases} T(t) = \frac{be^{at} + (aT_i - b)e^{at_0}}{ae^{at}} \\ a = \frac{\lambda S}{mc} \\ b = \frac{Hf + \lambda S T_0}{mc} = \frac{Hf}{mc} + aT_0 \end{cases} \tag{6}$$

The only unknowns appearing in Eq. (6) are the constant a that is the inverse of time constant of heat transfer, the dissipation power Hf and the heat capacity c, all of which are experimentally determined.

2.3. Dissipation power of cartilage obtained with uniaxial compression test

Human cartilage samples ($n=6$) were punched (8 mm diameter) from the femoral head of donors who have undergone hip arthroplasty (Centre Hospitalier Universitaire Vaudois Ethics Committee Protocol # 264/12). The samples were taken from different sites, three samples were punched close to the site of degeneration (<2 cm), and the others more than 2 cm