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Short communication

# Poisson's ratio of bovine meniscus determined combining unconfined and confined compression

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ABSTRACT

Poisson's ratio has not been experimentally measured earlier for meniscus in compression. It is however an important intrinsic material property needed in biomechanical analysis and computational models. In this study, equilibrium Poisson's ratio of bovine meniscus ($n = 6$) was determined experimentally by combining stress-relaxation measurements in unconfined and confined compression geometries. The average Young's modulus, aggregate modulus and Poisson's ratio were 0.182 ± 0.086 MPa, 0.252 ± 0.089 MPa and 0.316 ± 0.040, respectively. These moduli are consistent with previously determined values, but the Poisson's ratio is higher than determined earlier for meniscus in compression through biomechanical modelling analysis. This new experimentally determined Poisson's ratio value could be used in the analysis of biomechanical data as well as in computational finite element analysis when the Poisson's ratio is needed as an input for the analysis.



## 1. Introduction

Meniscus plays an important role in the knee joint to distribute and absorb forces. This role is strongly affected by the biomechanical properties of the tissue. Certain elastic, viscoelastic and poroelastic biomechanical properties of meniscus have been characterized (Danso et al., 2015; Pereira et al., 2014; Sweigart et al., 2004; Tissakht and Ahmed, 1995). However, experimentally measured Poisson's ratio has never been presented for meniscus in compression. In experimental biomechanical testing, the Poisson's ratio is required for instance when calculating the Young's modulus from indentation testing (Fig. 1). Also in finite element modelling simulating biomechanical behaviour of soft tissues, the Poisson's ratio affects the results (Fig. 2).

Some attempts have been made to determine the compressive Poisson's ratio of meniscus using finite element optimization from creep response (Sweigart et al., 2004), determining the mean Poisson's ratio for bovine meniscus between 0 and 0.01 depending on the location of meniscus. Similar values were also presented for different species including baboon, canine, human, lapine and porcine, with the highest reported mean value of 0.08 at the anterior segment from the tibial aspect of lapine meniscus (Sweigart et al., 2004; Sweigart and Athanasiou, 2005). However, none of these values were directly measured from experiments. Goertzen et al. determined experimentally the Poisson's ratio of meniscus being close to 1 (Goertzen et al., 1997), but the measurements were done in the tension. Values of the Poisson's ratio in tension are typically much higher than those in compression.

The aim of this study was to determine the bulk equilibrium Poisson's ratio of bovine meniscus by the combination of stress-relaxation tests in unconfined and confined compression measurement geometries. This approach has been shown earlier to produce the same Poisson's ratio with direct optical measurements of articular cartilage (Korhonen et al., 2002).

## 2. Methods

### 2.1. Sample preparation

Mature bovine knee joints were obtained from a local slaughterhouse and stored at −25 °C until the experiment. Prior to the biomechanical tests, menisci were thawed in water bath at room temperature (21 °C). Cylindrical samples ($n = 6$) were prepared with a biopsy punch and a razor blade from random locations of both lateral and medial menisci. First, using a biopsy punch (diameter = 4 mm), a cylindrical plug was cut perpendicularly from the

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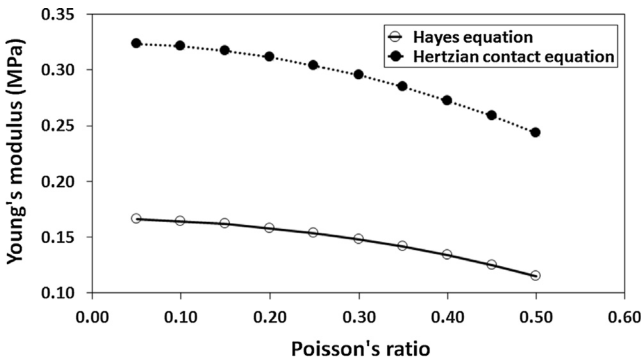


**Fig. 1.** Examples of the effect of Poisson's ratio in the analysis of Young's modulus from indentation testing. Indentation moduli have been analyzed with Hayes equation (for plane-ended indenter (Hayes et al., 1972)) and Hertzian contact equation (for spherical indenter) (Fischenich et al., 2018)), and plotted against Poisson's ratio. Hayes equation ($\boldsymbol{E_s} = \frac{(1-\boldsymbol{v}_1^2)\pi \boldsymbol{a}\boldsymbol{E}_1}{2\boldsymbol{\kappa h}}$) with $a$ = 0.5 mm, $h$ = 2.5 mm, $\boldsymbol{E}_1$ = 0.83 MPa, $\boldsymbol{\kappa}$ is Poisson's ratio specific (Hayes et al., 1972). Hertzian contact equation ($\boldsymbol{E_s} = \frac{(1-\boldsymbol{v}_1^2)}{\left(\frac{4\boldsymbol{a}^{1/2}\boldsymbol{d}^{3/2}}{3\boldsymbol{F}}\right)-\left(\frac{1-\boldsymbol{v}_2^2}{\boldsymbol{E}_2}\right)}$) with $\boldsymbol{v}_2$ = 0.3, $a$ = 0.80 mm, $d$ = 0.25 mm, $\boldsymbol{E}_2$ = 210 GPa, $F$ = 0.048 N. $\boldsymbol{E_S}$ = Young's modulus of the tissue, $\boldsymbol{E}_1$ = stress-strain ratio from experiments, $\boldsymbol{E}_2$ = Young's modulus of indenter, $\boldsymbol{v}_1$ = Poisson's ratio of tissue, $\boldsymbol{v}_2$ = Poisson's ratio of indenter, $\boldsymbol{a}$ = radius of indenter, $\boldsymbol{\kappa}$ = theoretical scaling factor (Hayes et al., 1972), $\boldsymbol{h}$ = tissue thickness, $\boldsymbol{d}$ = indentation depth, $\boldsymbol{F}$ = applied force.

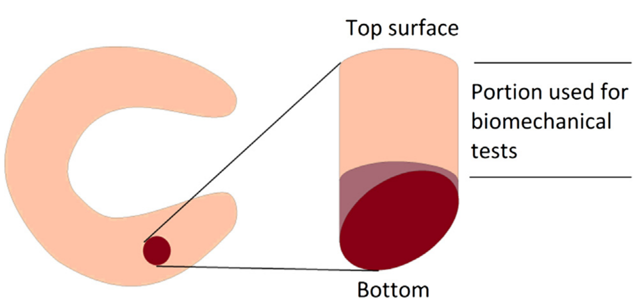


**Fig. 3.** Schematic of meniscus showing a cylindrical plug and the portion used for biomechanical testing.

surface to the bottom of the tissue (Fig. 3). This results in a cylindrical disc having a horizontally flat surface and a slanted bottom because of the wedge shape of meniscus (Fig. 3). The superficial surfaces of the samples were then kept intact, and the uniform thickness of the samples was obtained by cutting the samples from the slanted bottom. The thickness (1.54 ± 0.31 mm) was measured with a digital caliper and the diameter (3.82 ± 0.02 mm) with a stereomicroscope.

### 2.2. Biomechanical testing

Biomechanical testing was conducted by using a custom-made material testing system equipped with a high precision load cell (model 31/AL311AR, Honeywell, Columbus, OH, USA; resolution: 0.005 N) and an actuator (PM1A1798, Newport Corporation, Irvine, CA, USA; resolution: 0.1 μm) (Korhonen et al., 2002). For the unconfined compression measurements, the samples were placed between an upper steel rod and the bottom of the measuring chamber filled with phosphate buffered saline (Fig. 4). For the confined compression measurement, the samples were placed into a cylindrical metallic chamber sealed at the bottom, and the upper meniscal surface was in contact with a porous platen. The only means of fluid flow was through the porous platen at the top. Unconfined compression measurements were first conducted for

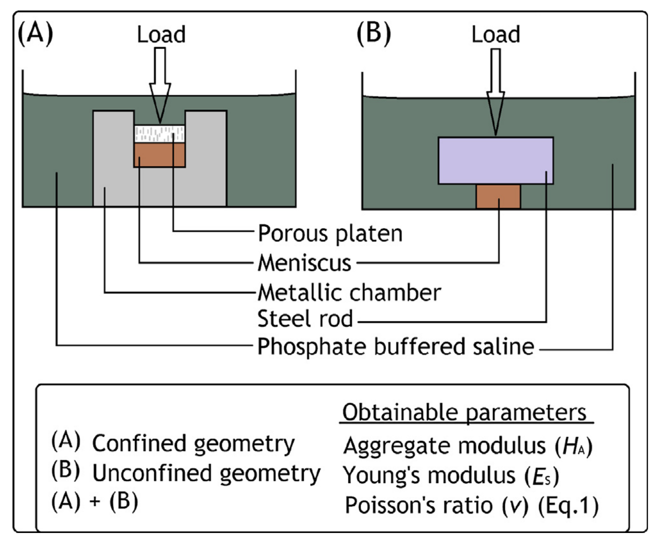


**Fig. 4.** Schematic of experimental set-up with parameters obtained. Confined compression measurement geometry (A) and unconfined compression measurement geometry (B) were combined to determine the Poisson's ratio.

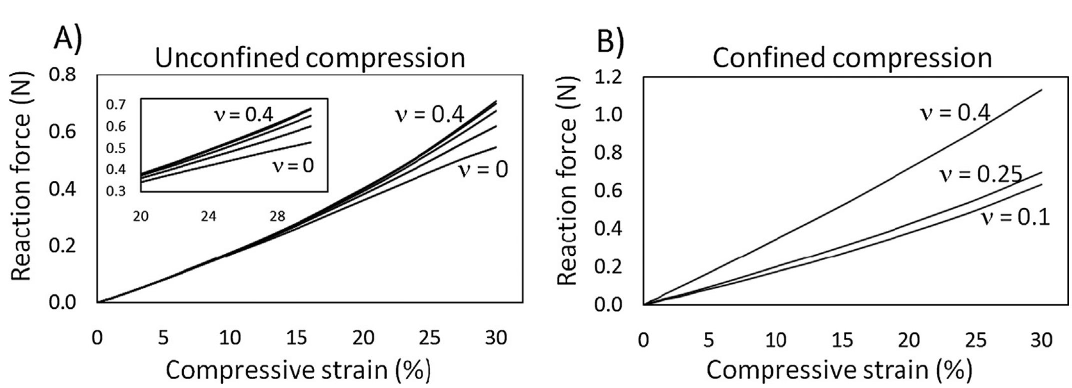


**Fig. 2.** Examples of the effect of Poisson's ratio in finite element analysis. Cylindrical-shaped Neo-Hookean hyperelastic sample of 1 mm in radius and 1 mm in height, and meshed with axisymmetric 4-node elements (CAX4), was compressed by 30% of its original thickness in unconfined (A) and confined (B) compression geometries. The bottom of the sample and the axis of symmetry were fixed in axial direction and lateral direction, respectively. In addition to these, in confined compression, the movement of the sample edge was restricted in the lateral direction. The Young's modulus ($E$) was 0.5 MPa and the Poisson's ratios ($\nu$) were between 0 and 0.4. By calculating the shear ($\mu$) and bulk ($\kappa$) moduli from $E$ and $\nu$, the implemented material constants $C_{10}$ and $D_1$ of the strain energy density function can be calculated as follows: $C_{10} = \frac{\mu}{2} = \frac{E}{4(1+\nu)}$; $D_1 = \frac{2}{\kappa} = \frac{6(1-2\nu)}{E}$. Static analysis was conducted with nonlinear geometry (nlgeom) in Abaqus 6.13 (Dassault Systèmes, Providence, RI, USA).

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