EXPERIMENTAL AND NUMERICAL VALIDATION OF NOVEL ARTHROSCOPIC INDENTATION INSTRUMENT FOR MEASUREMENT OF CARTILAGE STIFFNESS

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INTRODUCTION: Degradation of proteoglycans (PGs) and disruption of collagenous network are typical signs of incipient osteoarthrosis. Both processes impair biomechanical properties of articular cartilage (AC) and may be determined by mechanical measurements. Easiness of use, accuracy and reproducibility of the measurements and a low risk of damaging AC are the main qualities demanded from a clinical instrument. We have designed arthroscopic indentation instruments for the measurement of stiffness in thick (2-5 mm) [1] and thin (<2 mm) [2] cartilage. Measurements with these instruments in small animal joints were laborious to accomplish in a correct and reproducible way. In this study, we modified the original instrument [1] to better fulfil clinical requirements. The new instrument was validated using elastic isotropic and transversely isotropic finite element (FE) models of AC and experimental tests with elastomer samples and bovine knee AC.

MATERIALS AND METHODS: Original arthroscopic indentation instrument [1] is equipped with a plane-ended indenter and a reference plate (Fig. 1a). The novel instrument consists of a small spherical-ended indenter and a small reference plate (dia.=3 mm) (Fig. 1b).

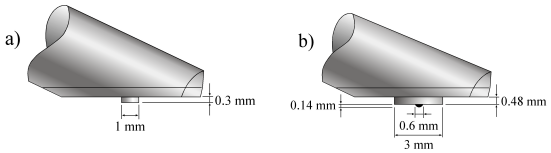

Figure 1. Schematic presentation of the original (a) and novel (b) indentation instruments.

Numerical analyses, used for simulating the instantaneous arthroscopic measurements, were conducted using a commercial FE package (Abaqus v.5.8, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA). The axisymmetric incompressible elastic model consisted of 8-node biquadratic elements (CAX8) of the indented material (cartilage or elastomer) and subchondral bone (E=1 GPa, n=0.3). The indenter and the reference plate were modeled as analytical rigid bodies. Elastic isotropic and transversely isotropic models were used in simulations. The whole model consisted of 1014 elements.

The manual pressing force for the instrument was optimized using elastic isotropic FE model. The goal was to find as small force as possible to minimize the risk of cartilage damage without endangering reliability of the measurements. FE analyses were carried out using 10-12 different pressing forces (0.25-10 N) and three different values for tissue instantaneous (n=0.49) dynamic modulus (E) (5, 10 and 20 MPa).

The effect of material thickness on the indenter force was investigated using both numerical analysis and experimental tests. Experimental tests were carried out using elastomer samples (n=8, E_{dyn}=4.6±0.3 MPa and thickness=0.5-6.0 mm). Elastomer samples were also measured with the original instrument [1]. FE analyses were conducted using elastic isotropic FE model having thickness values and the mean Young's modulus obtained from experimental tests.

The capability of the novel instrument to estimate stiffness of bovine knee joint AC was evaluated *in situ*. After *in situ* measurements, cartilage samples (n=29) were detached from the bone and tested dynamically (17.0 kPa pre-stress, 10% instantaneous compression, 2 mm/s) in unconfined compression.

To describe the effect of collagenous network, with high tensile stiffness, on the instantaneous response in indentation and unconfined geometry, transversely isotropic layers (comprising 0-100% of cartilage thickness) were included into the model using engineering constants (E_{11}=15 MPa, E_{33}=5 MPa, n_{31}=0.49, n_{12}=1-0.5(E_{11}/E_{33}), G_{13}=7.5 MPa) [3].

RESULTS: FE analyses indicated that, after the full contact of the reference plate, the indenter force was linearly dependent on the pressing force (Fig. 2a). Therefore, 3 N was chosen to represent the optimal (smallest reliable) pressing force for the novel instrument.

Experimental measurements of elastomers revealed that the effect of tissue thickness on the indentation response was reduced with the novel instrument when compared to the original instrument (Fig. 2b)

Indenter force correlated significantly (r=0.766, n=29, p<0.001) with the dynamic modulus of cartilage measured in unconfined compression (Fig. 3a). The novel instrument was optimal for measuring soft (E_{dyn}<10 MPa) cartilage (r=0.893, n=16, p<0.001) (Fig. 3b). Coefficient of variation (CV%) for cartilage measurements was 5.0%.

FE analyses indicated that the effect of transverse stiffness of deep cartilage (depth>40% of cartilage thickness) was minimal on the indentation response (Fig. 3c). The reference measurements under unconfined compression conditions, however, were influenced more significantly also by the transverse modulus of deep cartilage (Fig. 3d).

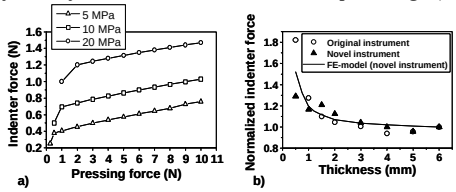

Figure 2. Indenter force of the novel instrument (elastic isotropic FE model) as a function of the pressing force for three material stiffness (5, 10 and 20 MPa) (a). The experimentally determined normalized indenter force for the original instrument as well as both experimentally and numerically (elastic isotropic FE model) determined indenter forces for the novel instrument as a function of the elastomer thickness (b).

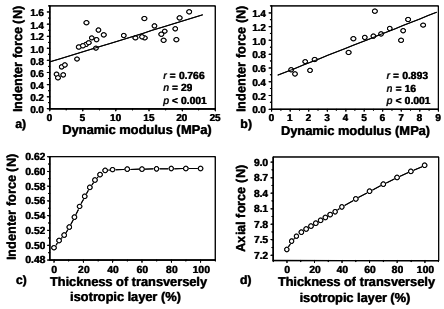

Figure 3. Experimental correlations between the instantaneous indenter force of the novel instrument and the cartilage dynamic modulus in all samples (a) or soft samples (E_{dyn}<10 MPa) (b). FE simulation on the effect of the thickness of elastic transversely isotropic layer, with high transverse tensile stiffness, on the indentation (c) and unconfined compression (d) responses.

DISCUSSION: The novel instrument was less dependent on the material thickness than the original one. Especially, the new instrument was sensitive in predicting stiffness of soft cartilage. This may be advantageous, since in clinical work, properties of soft degenerated cartilage are of major interest. FE analyses revealed that the superficial tangential collagenous layer with high transverse tensile stiffness is an important determinant for the AC stiffness, as measured by the indentation instrument. The reference measurements in unconfined compression, however, were strongly influenced also by the transverse properties of deep tissue. This may partially explain the slightly nonlinear relation between the indenter force and dynamic modulus found experimentally (Fig. 3a).

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