Novel Technique to Map the Biomechanical Properties of Entire Articular Surfaces Using Indentation to Identify Osteoarthritis-like Regions

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Introduction: It is challenging to identify and grade degenerated regions of the entire articular surface both quantitatively and non-destructively. Therefore, the objective of this study was to investigate the ability of a novel technique to automatically characterize mechanical properties of entire articular surfaces in indentation to rapidly discriminate between damaged articular cartilage (AC) and healthy ones.

Methods: The distal femurs of eight human tissue donors with research consent aged 46 to 64 years were obtained from RTI Surgical. Articular lesions were graded with the visual ICRS classification system (Fig. 1A) [1]. Mechanical properties were mapped in vitro, using a novel technique allowing for automated alignment and mapping of articular surfaces (Mach-1 v500css, Biomomentum Inc., Laval, Canada). Subsequently, the thickness was measured with an adapted version of the needle technique [2]. The instantaneous modulus (IM) at each position (Fig. 1B) was obtained by fitting the load-displacement curve (with corresponding thickness) to an elastic model in indentation [3]. Osteochondral cores were harvested from healthy (ICRS Grade 0) and osteoarthritis (OA)-like regions (ICRS Grade > 0). From those cores, 45 were isolated for histological assessment and 21 were tested in unconfined compression where mechanical properties were extracted from the stress relaxation curve [4].

Results: Average mappings of the IM (Fig. 2A) were created from healthy regions (ICRS Grade 0) and where OA-like regions were identified mechanically, they were wider than the regions identified by visual assessment (Blue-green regions in Fig 2B). Unpaired t-tests revealed a significant decrease of the IM in indentation (p = 0.04, Fig. 3A) and of the fibril modulus in unconfined compression (p = 0.02, Fig. 3B) in OA-like vs. healthy cartilage. A strong correlation ($R^2 = 0.7035$, $p < 0.0001$) was observed between the mechanical properties measured in indentation and in unconfined compression (Fig. 3C).

Discussion: Our results clearly demonstrate that mapping biomechanical properties of articular cartilage surfaces using indentation identifies precisely and non-destructively OA-like regions on the entire articular surface. We are currently comparing with histology to grade healthy vs OA-like properties. This indentation mapping technique provides non-destructive measurements of the mechanical properties of the entire articular surface and would be of great use in the identification of wear patterns in osteoarthritis progression and for use in cartilage repair studies.

Significance: Indentation on intact articular surfaces has many advantages including the ability to perform subsequent analyses like histology and testing at multiple sites. Therefore, this novel indentation technique generates mapping of the mechanical properties that could be used in any type of study that requires knowing the distribution of the mechanical properties on the entire articular surfaces such as the identification of wear patterns in osteoarthritis progression or in cartilage repair studies.

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Figure 1. A) Example of visual ICRS scoring of the articular surfaces of human (64 years old, Male) left knee joint. Regions with an ICRS Grade > 0 are circled; B) Sample with the indentation and thickness position grid superposed.

Figure 2. A) Average mapping (only healthy articular cartilage) of the instantaneous modulus of 8 knee joints (300 positions total); B) Example of the mapping of the instantaneous modulus to identify OA-like AC. Logarithmic scale from 1 to 20 MPa.
Figure 3. Instantaneous modulus obtained in indentation (A) and fibril modulus obtained in unconfined compression (B) for OA-like and healthy AC. (* p value < 0.05, N=21); C) Significant correlation between the instantaneous modulus and fibril modulus.

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