NOVEL TECHNIQUE TO MAP THE BIOMECHANICAL PROPERTIES OF ENTIRE ARTICULAR SURFACES USING INDENTATION TO IDENTIFY EARLY OSTEOARTHRITIS-LIKE REGIONS

S. SIM\textsuperscript{1, 2}, A. CHEVRIER\textsuperscript{1}, M. GARON\textsuperscript{2}, E. QUENNEVILLE\textsuperscript{2} AND M.D. BUSCHMANN\textsuperscript{1}

1. BIOMEDICAL & CHEMICAL ENGINEERING, ECOLE POLYTECHNIQUE DE MONTREAL, MONTREAL, QC, CANADA
2. BIOMOMENTUM INC., LAVAL, QC, CANADA
Mechanical testing of articular cartilage is a useful outcome measure in studies of cartilage degeneration and cartilage repair.

Mechanical testing can be done in different experimental configurations:

- Indentation
- Compression
- Shear
- Torsion
- Tension
- Bending
PRACTICAL ADVANTAGES OF INDENTATION

- Cartilage need **not be harvested** from the articular surface
- **Minimal disruption** of the articular surface
- **Maintains** the mechanical environment of the cartilage layer and its interaction with the subchondral bone
- Testing **multiple** sites

However

Indentation requires the compression axis aligned **perpendicular** to the articular surface.

Mathematical **models** are more **complex** in indentation with a spherical indenter.

*Picture from: http://www.kneeclinic.info/*
TECHNIQUE OVERVIEW

• Automated indentation mapping
• Automated thickness mapping
• Analysis of thickness
• Analysis of instantaneous modulus
AUTOMATED INDENTATION MAPPING

- spherical indenter for a new automated indentation mapping
- multiaxial load cell – uses Fx, Fy and Fz to calculate the perpendicular force
- 3-axis mechanical tester – uses 3 displacement components to provide a perpendicular displacement based on the surface orientation

Measures the contact coordinates of the predefined position

Contact coordinates \((x, y, z)\) of predefined positions and 4 surrounding positions

Surface orientation \((\theta_z)\)

Perpendicular force/displacement vs time

Thickness is missing
AUTOMATED INDENTATION MAPPING

- spherical indenter for a new automated indentation mapping
- multiaxial load cell – uses Fx, Fy and Fz to calculate the perpendicular force
- 3-axis mechanical tester – uses 3 displacement components to provide a perpendicular displacement based on the surface orientation

Measures the contact coordinates of surrounding positions

Contact coordinates \((x,y,z)\) of predefined positions and 4 surrounding positions

Surface orientation \(\theta_z\)

Perpendicular force/displacement vs time

Thickness is missing
AUTOMATED INDENTATION MAPPING

- spherical indenter for a new automated indentation mapping
- multiaxial load cell – uses Fx, Fy and Fz to calculate the perpendicular force
- 3-axis mechanical tester – uses 3 displacement components to provide a perpendicular displacement based on the surface orientation

Calculates surface orientation using the measured contact coordinates
AUTOMATED INDENTATION MAPPING

- spherical indenter for a new automated indentation mapping
- multiaxial load cell – uses Fx, Fy and Fz to calculate the perpendicular force
- 3-axis mechanical tester – uses 3 displacement components to provide a perpendicular displacement based on the surface orientation

Performs a perpendicular indentation at the predefined position

Contact coordinates (x,y,z) of predefined positions and 4 surrounding positions

Surface orientation ($\theta_z$)

Perpendicular force/displacement vs time

Thickness is missing
AUTOMATED INDENTATION MAPPING

- spherical indenter for a new automated indentation mapping
- multiaxial load cell – uses Fx, Fy and Fz to calculate the perpendicular force
- 3-axis mechanical tester – uses 3 displacement components to provide a perpendicular displacement based on the surface orientation

Performs a perpendicular indentation at the predefined position

Contact coordinates (x, y, z) of predefined positions and 4 surrounding positions
Surface orientation (θz)
Perpendicular force/displacement vs time

Thickness is missing
AUTOMATED THICKNESS MAPPING

There is a small load increase as the needle reaches the articular surface.

Position of the cartilage surface
Position of the subchondral bone
Vertical force/displacement vs time
Thickness can be obtained

Technique adapted from Jurvelin et al., 1995
Then there is a sharp load increase as it reaches the subchondral bone.

Technique adapted from Jurvelin et al., 1995.
ANALYSIS – THICKNESS

Thickness = vertical distance x cosine (surface orientation)

Surface orientation

Cartilage surface

Vertical Distance

Subchondral bone
ANALYSIS – INDENTATION

Elastic Model in Indentation\(^2\) (Hayes, 1972) → Using the known thickness → Instantaneous Modulus (MPa)

\[
E = \frac{P}{H} \cdot \frac{(1 - \nu^2)}{2ak\left(\frac{a}{h} \cdot \nu\right)}
\]
It is challenging to identify and grade degenerated regions of the entire articular surface both quantitatively and non-destructively.

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 and healthy articular cartilage.
SAMPLES

- Complete articular surfaces
- 8 distal femurs (Right & Left knees)
- 4 human tissue donors with research consent
- Aged 46 to 64 years
- Obtained from a tissue bank (RTI Surgical, Florida, USA)
METHOD OVERVIEW

**Input:**
Entire articular surface

**Step 1**
Visual grading using ICRS system

**Step 2**
Automated Indentation Mapping

**Step 3**
Extraction of osteochondral cores

**Step 4**
Automated Thickness Mapping

**Output:**
ICRS grading

**Output:**
Perpendicular force vs. position curve at each position

**Output:**
Osteochondral Cores

**Output:**
Thickness curve at each position

**Step 3.1**
Unconfined compression

**Step 3.2**
Histological assessment
SAMPLE PREPARATION

1. Articular surfaces were attached to a testing chamber

2. Filled with PBS

3. Equipped with a camera-registration system (~1 mm registration resolution) (Biomomentum, Canada)

4. A position grid was superimposed on the image of the sample
STEP1 – VISUAL GRADING

Articular surfaces were visually graded using ICRS system\(^3\):

- ICRS 0 (visually normal, outside circled regions)
- ICRS > 0 (visually abnormal, inside circled regions)
MECHANICALLY-CONTROLLED SURFACE MAPPING

Sample

Camera

Picture (1280x960 pixels)

Position grid superimposed

Converted in units of length (mm)

MACH-1

Example of sheep femoral condyles
### STEP 2 – AUTOMATED INDENTATION MAPPING

<table>
<thead>
<tr>
<th>Device</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach-1 v500css from Biomomentum Inc.</td>
<td>Spherical indenter</td>
</tr>
<tr>
<td>Multiaxial mechanical tester</td>
<td>Radius of 3 mm</td>
</tr>
</tbody>
</table>

Perpendicular force vs. position curve at each position to calculate the instantaneous modulus.
STEP 3 – EXTRACTION OF OSTEOCHONDRAL CORES

- Harvested from healthy regions (ICRS Grade 0)
- Harvested from OA-like regions (ICRS Grade > 0)
- 72 were isolated for histological assessment
- 21 were tested in unconfined compression
### STEP 4 – AUTOMATED THICKNESS MAPPING

<table>
<thead>
<tr>
<th>Device</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach-1 v500css from Biomomentum Inc.</td>
<td>Intradermal Bevel Needle from Precision Glide</td>
</tr>
<tr>
<td>Multiaxial mechanical tester</td>
<td>Needle size of 26G 3/8”</td>
</tr>
</tbody>
</table>

Force vs. position curve at each position to calculate the thickness.
RESULTS – THICKNESS MAPPING

- Visually abnormal cartilage inside circled region.
- Pattern of thickness is symmetric for right and left joint of the same donor.
- Thickness are in agreement with previously reported data for human femoral cartilage\(^4,5\).
- Thickness patterns do not correlate with visual assessment of abnormal cartilage.
RESULTS – INSTANTANEOUS MODULUS

- Pattern of instantaneous modulus are symmetric for right and left joint of the same donor.

- Degenerated regions have low instantaneous modulus (between 0.2 and 3 MPa, blue-green regions in the figure)

- Instantaneous modulus measured in indentation reveals and quantifies the visually identified abnormal regions.

- Instantaneous modulus shows degradation patterns that often extend beyond the visual lesion boundaries.
RESULTS – HISTOLOGY CORRELATION

- **Mankin score**: The Safranin O/Fast Green stained section showed decrease GAG content for decreased instantaneous modulus.

- The histological slides appeared normal for Mankin scores between 0 and 2 (Fig. 5A).
- Decreased Safranin O staining and structural alterations were apparent in the superficial zone for Mankin scores between 3 to 5 (Fig. 5B).
- Clefts and reduced Safranin O staining for Mankin scores greater than 6 (Fig. 5C).
- Instantaneous Modulus correlated weakly but significantly with the Mankin score \((r = -0.39, p=0.0007)\)
Mankin scores were similar in visually normal regions adjacent to the defects and in regions far from the defects, while the instantaneous modulus was significantly lower in visually normal regions adjacent to the defects compared to regions far from the defects.

Instantaneous modulus is much more sensitive than histological methods to reveal early cartilage changes/degeneration.
RESULTS – MECHANICAL CORRELATION

- Unconfined compression:
  - Strong correlations were observed between the mechanical properties measured in indentation and in unconfined compression:
    - Fibril Modulus $E_f$ ($r = 0.84$, $p<0.0001$)
    - Equilibrium Modulus $E_q$ ($r = 0.67$, $p=0.0009$)

As expected, the instantaneous modulus in indentation correlates best with the fibril modulus in unconfined compression because it is the response of the fibril network that is solicited in an instantaneous compression.
DISCUSSION

- Excluding sample preparation time, the completion of each pair of thickness and indentation mapping takes:
  - 1 minute/position of machine time
  - 30 minutes/pair of joints for data post-processing

Advantageous compared to histology and unconfined compression which require several days or weeks and only provide information on specific locations that are consumed by the analyses.
CONCLUSION

• We have demonstrated the ability of this novel automated indentation mapping technique to map the biomechanical properties of full articular surfaces and to reveal its degenerated regions

  ✔ Rapidly
  ✔ Sensitively
  ✔ Non-destructively

• This automated indentation mapping technique could be of great value in the identification of wear patterns in OA progression and in cartilage repair studies.
ACKNOWLEDGMENTS

Funding provided by the National Sciences and Engineering Research Council (NSERC), the Fonds québécois de la recherche sur la nature et les technologies (FQRNT) and Biomomentum Inc.

We acknowledge the technical contributions of:

• Alexandre Torres
• François Marcoux
• Geneviève Picard
• Marie-Hélène Boulanger
• Sylvain Gaufrès
REFERENCES


2. Hayes 1972, J Biomech 5:541

3. www.cartilage.org; ICRS Cartilage Injury Evaluation Package


QUESTIONS