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

S. Sim1,2, A. Chevrier1, M. Garon2,E. Quenelle2 and M.D. Buschmann1

1. Biomedical & Chemical Engineering, Ecole Polytechnique de Montreal, Montreal, QC, Canada 2. Biomomentum Inc., Laval, QC, Canada

Introduction

The identification and quantitative grading of early degenerated regions over an entire articular surface remains a challenging quest. The objective of this study was to investigate the ability of a novel technique to automatically characterize mechanical properties of entire human articular surfaces in indentation in order to rapidly and non-destructively discriminate between damaged and healthy articular cartilage regions.

Significance: Indentation on intact articular surfaces has many advantages including the ability to maintain the natural mechanical environment of the cartilage during testing while allowing subsequent analyses. The mechanical mapping of articular surfaces opens the door to new type of analysis where the distribution of the mechanical properties (not only the local properties) are studied. This could be particularly useful in the identification of wear patterns in OA progression or in cartilage repair studies.

Methods

1. Human Distal Femurs (N=8)

- Complete articular surfaces from 8 distal femurs were obtained from RTI Surgical, FL.
- Articular surfaces were attached to a testing chamber filled with PBS and equipped with a camera-registration system (“1 mm registration resolution”) (Biomomentum, Canada). A position grid was superimposed on the image of the sample (Fig. 1).
- Articular surfaces were visually graded using ICRS system1:
  - ICRS 0 (visually normal, outside circled regions in Fig. 6 & 7)
  - ICRS > 0 (visually abnormal, inside circled regions in Fig.6 & 7)

2. Ex Vivo Mechanical Assessment of Distal Femurs

Automated Indentation Mapping

- A spherical indenter (radius = 3 mm) for this new automated indentation technique (Fig. 2).
- A multiaxial load cell uses Fx, Fy and Fz to calculate the normal force.
- A 3-axis mechanical tester (Mach-1, Biomomentum) uses 3 displacement components simultaneously to provide perpendicular displacement based on the measured surface orientation (Fig. 3).

Steps performed at each position:
1) Measure the contact coordinates at a predefined position (Fig. 1)
2) Measure the contact coordinates of 4 surrounding positions
3) Calculate surface orientation using the contact coordinates
4) Perform perpendicular indentation and measures the normal force (Fig 4)

Automated Thickness Mapping

- A needle probe replaces the spherical indenter.
- A load cell uses Fz to calculate the force (Fig. 5).
- Thickness measurement with an adapted version of the needle technique2.
- Mapping of cartilage thickness (vertical distance) over the entire articular surface.
- Cartilage thickness was calculated using the surface orientation previously obtained.

Thickness = Vertical distance x cosine (surface orientation)

Instantaneous Modulus

- The instantaneous modulus at each position was obtained by fitting the load-displacement curve (with corresponding thickness) to an elastic model in indentation3.

Conclusion

Contrary to what is usually required for traditional biomechanical testing (i.e. individual sample harvesting, visual orientation of the sample surface perpendicularly to compression axis, sample preservation causing possible mechanical alteration), this technique does not require intervention which are costly and time-consuming during the test. This reduces considerably the sources for possible measurement errors and allows for high resolution mapping of the entire articular surface.

Those results clearly demonstrate the capabilities of this novel automatic indentation technique to rapidly, objectively and non-destructively map the biomechanical properties of full articular surfaces and to reveal its degenerated regions.

This automatic indentation mapping technique would be of great value in the identification of wear patterns in OA progression and in cartilage repair studies.

Results

Thickness Mapping

<table>
<thead>
<tr>
<th>Age</th>
<th>Thickness (mm)</th>
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<tbody>
<tr>
<td>46 year old - Female</td>
<td>2.55 ± 0.51 (48)</td>
</tr>
<tr>
<td>49 year old - Female</td>
<td>1.70 ± 0.55 (80)</td>
</tr>
<tr>
<td>58 year old - Male</td>
<td>2.07 ± 0.60 (67)</td>
</tr>
<tr>
<td>64 year old - Male</td>
<td>2.19 ± 0.61 (48)</td>
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</tbody>
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Instantaneous Modulus Mapping

<table>
<thead>
<tr>
<th>Age</th>
<th>Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46 year old - Female</td>
<td>5.03 ± 2.07 (47)</td>
</tr>
<tr>
<td>49 year old - Female</td>
<td>3.61 ± 2.90 (78)</td>
</tr>
<tr>
<td>58 year old - Female</td>
<td>4.92 ± 3.26 (100)</td>
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<tr>
<td>64 year old - Male</td>
<td>4.83 ± 3.81 (48)</td>
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Acknowledgments

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References