Comparing Finite Element and Contact Modeling Techniques to Evaluate Radiocarpal Joint Mechanics

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ABSTRACT INTRODUCTION:
Secondary osteoarthritis (OA) as a result of joint injury is a significant problem. For the wrist in particular, scapholunate ligament dissociation is a commonly occurring injury. This has been known to progress to advanced collapse (SLAC wrist) with radiocarpal OA [1]. While the pathomechanics leading to the onset of OA are not clearly understood, changes in kinematics and contact mechanics (elevated joint contact pressure) with injury are believed to be causative factors. Comparing changes in joint mechanics between normal and injured wrists may help us better understand the progression of OA and improve the efficacy of corrective measures. Several techniques exist to evaluate joint mechanics. Of these, 3D image-based computational modeling is very useful to determine in vivo joint mechanics. Finite element modeling (FEM) is the most common and widely used technique because of the ability to obtain 3D stresses and strains. However, generating a quality FEM and solving the complex nonlinear contact problem is time consuming. To evaluate changes in joint mechanics, it is sufficient to look at surface contact mechanics: contact areas, forces, and pressures distributions. This MRI-based surface contact modeling (SCM) mesh generation is relatively simple and the solution computationally efficient [2]. Therefore the objective of this study was to compare radiocarpal joint mechanics from FEM and SCM to determine the level of modeling complexity required to obtain clinically relevant data.

METHODS:
Data analysis was performed on the normal wrist of one human subject. The protocols were approved by the University of Kansas Medical Center’s human subjects committee. A 3T clinical MRI scanner was used to obtain two sets of images. The normal wrist was first imaged with the hand relaxed (0.5 mm slice thickness and 0.15 mm in-plane pixels). Then images were acquired during active light grasp (at half the resolution to reduce scan time). The high resolution images were used to construct the geometric radiocarpal joint models while image registration between image sets was used to determine carpal bone kinematics during functional loading (the low resolution images).

For SCM, the radius, lunate and scaphoid bones and their cartilage surfaces were segmented from the images using ScanIP (Simpleware Ltd, Exeter, UK). They were then wrapped with triangular facets to create surface models. The kinematics and surface models were then implemented in Joint_Model [3]. The region of model surface penetration yielded the contact area for each articulation. Local contact pressure was calculated from local interpenetration and material properties (effective cartilage modulus = 4 MPa, assuming 1 mm uniform thickness for each articular surface). Contact pressures were integrated over the contact area to obtain contact force.

For FEM cartilage only surfaces of the radius and carpal bones were segmented. Due to light grasp, the bones were assumed as rigid (undergoing negligible deformation). FEM meshes of four-node tetrahedral elements were constructed for the radius, lunate and scaphoid cartilages using ScanIP+FE. Mesh refinement was varied from 19,742-79,450 nodes for convergence check and radius, lunate and scaphoid cartilage meshes consisting of 125,105 nodes, 79,450 nodes, and 88,845 nodes respectively, were found to have sufficiently converged. Cartilage was represented as elastic, homogeneous and isotropic with elastic modulus = 4 MPa and Poisson’s ratio = 0.45. The bone-cartilage interfaces were rigidly constrained with the kinematic boundary conditions and frictionless contact was defined at the articulations. Analysis was performed using Abaqus 6.9 (Simulia Corp, Providence, RI) to obtain contact areas, contact forces and peak contact pressures.

Contact parameters were qualitatively and quantitatively compared between SCM and FEM modeling for both radiolunate and radioscaphoid articulations. Also direct contact area measures were used to verify modeling accuracy. Contact regions were segmented from the loaded scans to obtain the effective contact areas for each articulation.

RESULTS SECTION:
Qualitatively the size and location between SCM and FEM radiolunate and radioscaphoid contact correspond very well (Fig. 1).

Looking at contact parameters (Table 1), contact areas matched closely while contact force and peak contact pressure were lower for SCM. Both model contact areas closely matched directly measured contact areas.

Figure 1. Contact pressure distribution for radiolunate (a) and radioscaphoid (b) articulations on the radius fossa. Left shows SCM results and right shows FEM results. Orientation varies radially (R) from right to left and dorsally (D) from bottom to top.

Table 1. Comparison of contact parameters between SCM and FEM for radiolunate (RL) and radioscaphoid (RS) contact.

<table>
<thead>
<tr>
<th></th>
<th>RL</th>
<th>RS</th>
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<tbody>
<tr>
<td>Force (N)</td>
<td>11.023</td>
<td>7.860</td>
</tr>
<tr>
<td>Peak Pressure (MPa)</td>
<td>0.606</td>
<td>0.540</td>
</tr>
<tr>
<td>Area (mm²)</td>
<td>42.349</td>
<td>48.833</td>
</tr>
<tr>
<td>Direct Area (mm²)</td>
<td>40.171</td>
<td>53.583</td>
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DISCUSSION:
The study is ongoing and preliminary comparison between SCM and FEM looks very promising. Contact area matches the best. This is expected as contact area results from direct surface interaction. FEM results for peak pressure are reasonable and fall in the expected 1-3 MPa range. FEM used actual cartilage thickness from the image data while a uniform thickness was assumed for SCM (though the articular surface was the actual surface). Overestimation of cartilage thickness will result in lower strain values and therefore, lower contact pressure and force values. Variable thickness models can be implemented in the SCM software. Also, the surface models for SCM were decimated (80-95%) for the analysis to run in Joint_Model, resulting in lower geometric fidelity. This may have caused an averaging/lowering of the peak contact pressures and force values due to the fewer, more widely-spaced nodes. While FEM analysis can provide additional important information on internal stresses and strains, the SCM technique is simple and efficient and provides useful joint contact mechanics data. SCM may be made more reliable with geometric model refinement. Further work is needed to evaluate determinants of quantitative SCM accuracy.

SIGNIFICANCE:
The simplicity and efficiency of SCM can make calculation of in vivo joint mechanics data more feasible. SCM data appears to be sufficient to investigate joint abnormalities and pathologies.

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REFERENCES: