INTRODUCTION

Patellofemoral pain syndrome (PFPS) is a debilitating knee impairment and one of the most common causes of orthopaedic related physician visits each year [1] in the general as well as athletic populations. Despite highly concentrated research efforts, the etiology of the pain is not fully understood. Patellofemoral (PF) pain has been demonstrated to be associated with altered PF joint mechanics; however, an actual variation in joint contact stresses has not been established. These variations in contact stresses are key to improving clinical insights from which subject-specific rehabilitation or surgical interventions can be devised.

Cine-phase contrast (CPC) MRI is one of the techniques currently used to non-invasively quantify in vivo 3D joint motion [2]. Despite its sub-millimeter accuracy (<0.33mm/0.97°) and precision (<0.18°) [3], CPC is limited in its ability to provide 3D spatial data, due to subject stamina and time constraints. On the other hand, multi-plane cine (MPC) MRI generates 3D spatial data acquired over a movement cycle, requiring the same image acquisition time as CPC. Registering the 3D spatial data over a motion cycle will enable accurate animation of 3D cartilage and bone surfaces and thus, provide essential data in regards to dynamic cartilage contact patterns and stresses. Yet, the accuracy of such registration is unknown. Hence, the objective of this study was to develop and evaluate a methodology for registering high-resolution 3D MR static images with dynamic MPC images in order to quantify PF kinematics with the ultimate goal of defining PF joint contact mechanics.

METHODS

Ten healthy volunteers (3 males, 7 females) provided informed consent prior to participating in this IRB approved study. Each subject was asked to lay supine within the 3T MRI scanner (Philips Medical Systems, Best, NL). The subject’s knee was placed in a MRI-compatible jig that allowed rhythmic knee flexion-extension motion. During this motion, a dynamic CPC MR image set (x,y,z velocity and anatomic images over 24 time frames) was acquired [2]. Additionally, a 7-plane sagittal MPC image set was obtained. Next, the subject’s knee was placed in an 8-channel knee coil (with the leg in full extension) and high resolution, static 3D sagittal Gradient Recall (GRE) images were acquired.

PF kinematics were first derived through integration of the CPC velocity data and were expressed relative to anatomical coordinate systems defined for each bone [2]. Similarly, PF kinematics were defined using the transformation matrices from the 24 dynamic to static registrations for each bone and were subsequently expressed relative the same anatomical coordinate systems as the CPC kinematics (Figure 1). The accuracy of the registration was determined as the average absolute error between the CPC and MPC kinematics. Two such accuracies were defined. The first incorporated all 24 time frames and the second incorporated only the quasi-static (QS) images representing full extension and full flexion when change in knee angle over the time frame was
less than 2°. This was done because the high resolution static model could be animated based on the MPC kinematics or based on the CPC kinematics. To use the latter, a single time frame from the MPC kinematics needs to be registered to the static model. Once the static model is in the dynamic space, the CPC kinematics can be used to animate the model. Since the QS time frames provide the clearest data with minimal temporal averaging, these time frames provide the greatest accuracy for the single time frame registration.

RESULTS AND DISCUSSION
Average absolute errors using QS time frames were less than 0.8mm and 1.75° (Table 1), which is comparable to registration of a sparse static patellar model to a high quality 3D model (errors < 0.88mm and 1.75° [4]). The errors averaged over the QS times frames were lower than those averaged over all 24 time frames (Figure 2). Errors for patellar flexion and tilt were considerably higher than other degrees of freedom (DOF), indicating that the fitting algorithm might not have enough dynamic data to get a closer fit from the registration process for these DOF.

Other attempts at quantifying patellar kinematics have been performed using low resolution static MRI techniques [4] or biplane X-ray techniques [5]. Although static MRI scans give insights to PF contact patterns, they may not provide accurate contact stresses due to relaxation properties of the tissue. Exposing the patients to longer durations of X-ray radiation for dynamic data collection is also not desirable. Further, X-ray to 3D CT registration techniques still require a high resolution 3D static MR imag set in order to quantify cartilage contact mechanics, and the registration between the 3D static MRI and CT models likely would add further error to the currently reported accuracies. Compared to these studies, the current study employed dynamic in vivo data acquisition using non-invasive MRI scans. Currently, MPC images suffer from volume averaging artifact (spatial distortion) making the bony outlines difficult to segment during the high velocity time frames. This may have affected the registration fit as distorted regions were not segmented in an outline.

CONCLUSIONS
This study has demonstrated that registration of MPC images to a 3D static MRI model is a highly accurate method for establishing the kinematics of a 3D model and will enable the quantification of in vivo 3D joint contact mechanics. CPC remains an analytically simpler and more accurate technique for tracking kinematics as compared to the dynamic to static shape registration. Thus, for applications requiring rendering a 3D model throughout a movement, the most accurate approach is to register a single time frame (during the QS periods of movement) and use the kinematics derived through integration to animate the model. For such an application, sub-millimeter accuracies are still possible. However, further enhancements in registration accuracies are likely due to technological advancements in MRI data acquisition and registration. Thus, the dynamic to static shape registration may eventually obtain accuracies closer to those of the CPC technique (<0.33mm [3]).

REFERENCES

Table 1: Average absolute errors of the MPC (registration) kinematics compared with CPC (integration) kinematics. The first row represents the error averaged over all time frames and the second row the error averaged over the QS time frames.

<table>
<thead>
<tr>
<th></th>
<th>X (Medial)</th>
<th>Y (Posterior)</th>
<th>Z (Superior)</th>
<th>X (Extension)</th>
<th>Y (Varus)</th>
<th>Z (Tilt)</th>
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<tbody>
<tr>
<td>All</td>
<td>Avg 0.85</td>
<td>SD 0.62</td>
<td>Avg 1.02</td>
<td>SD 0.41</td>
<td>Avg 1.33</td>
<td>SD 0.71</td>
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<tr>
<td></td>
<td>Avg 2.63</td>
<td>SD 1.46</td>
<td>Avg 1.93</td>
<td>SD 0.80</td>
<td>Avg 3.24</td>
<td>SD 1.63</td>
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<tr>
<td>QS</td>
<td>Avg 0.67</td>
<td>SD 0.56</td>
<td>Avg 0.68</td>
<td>SD 0.42</td>
<td>Avg 0.78</td>
<td>SD 0.47</td>
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<tr>
<td></td>
<td>Avg 1.75</td>
<td>SD 0.76</td>
<td>Avg 1.16</td>
<td>SD 0.23</td>
<td>Avg 1.66</td>
<td>SD 0.86</td>
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