INTRODUCTION:
Many studies have attempted to understand the role of soft tissue structures and joint surface contact in providing stability to the knee joint. Clinically, weightbearing forces are believed to stabilize the joint during exercise. However, Torzilli et al. described an anterior neutral shift of the tibia caused by joint compressive loads, that was confirmed by Beynon for ACL-deficient knees, but not intact knees, questioning the benefit of weightbearing forces during exercise (1,6). These studies suggest that the shift is related to articular contact, however, no direct assessment of this contact has been possible in the in vivo or radiographic in vitro studies. In this study, we use in vivo MR imaging and an image-based motion tracking algorithm to determine 3D tibiofemoral motion in the loaded knee joint. In addition, MR images allow visualization of articular contact, menisci and ligaments during loading. Specifically, we test the hypothesis that anterior loads cause greater anterior displacement in the absence of joint compression than with partial weightbearing, and test for anterior neutral shift with axial loads.

MATERIALS AND METHODS:
Five healthy adult subjects participated in the study after providing informed consent with IRB approval (age: 29 ± 9.7 yrs.; wt: 71 ± 11 kg; ht: 175 ± 9 cm). One subject had history of knee injury, with a tear in the medial meniscus, treated by partial meniscectomy using an arthroscopic procedure five years prior to the study.

A loading device was designed to position the subject supine with an average flexion angle of 8°, depending on subject height, in a manner consistent with the KT1000 apparatus. The thigh was strapped in place and supports tightened against the femoral condyles to minimize medial/lateral motion and rotation during loading. An ankle-foot orthosis stabilized the ankle joint and allowed application of loads directed from the ankle toward the hip joint. Anterior drawer loads were applied through a strap around the tibia just below the tibial tubercle. Both axial and anterior loads were applied with pulleys and cords supporting stacks of lead weights. Subjects were instructed to relax and minimize muscle contractions. A custom-designed four-coil phased array receiver coil was integrated into the loading device (3).

Magnetic resonance images were obtained in the sagittal plane with a 3D fast gradient recalled echo (GRE) sequence (TE: 1.9, TR: 7, 1 Nex, Flip angle: 40°, time of scan 2.05 min.). A 256x256 matrix was used, with a field-of-view of 17 cm and slice thickness of 1.5 mm. Reference images were collected in the unloaded position, followed by image sets with axial loads of 225 N; combined axial and anterior loads of 225 and 107 N respectively; a repeated unloaded position; and an anterior load of 107 N alone. An identical field-of-view was used for each of the sequential positions.

An anatomic coordinate system was defined for each knee in the unloaded position by manually selecting nine fiducial points in sagittal and reconstructed axial images (4). Using a semi-automated segmentation algorithm, the femur and tibia were identified in the unloaded image set and their motion tracked to the sequential image sets, assuming they behaved as rigid bodies. The motion tracking algorithm involves random selection of feature points within bone volumes and deformable surrounding soft tissues. A minimization algorithm based on voxel intensity, gradient and mesh deformation energy is used to predict the motion of the rigid bones from one volume data set to subsequent sets (5). Translations and rotations of the femur and tibia in the global reference frame are expressed in anatomic coordinate systems using appropriate coordinate trans-formations. This approach has been validated to provide an accuracy of ± 0.39 mm and 0.38° for controlled motion of a cadaveric knee joint (4). For prediction of each loaded position, five sets of motion tracking results were averaged. Statistical analysis was performed to compare the six components of the tibiofemoral motion with axial load, combined loads, and anterior loads, relative to the previous unloaded position.

RESULTS:
MR images indicated anterior displacement of the tibia relative to the femur (Table 1), with the ACL appearing taut with the 107 N anterior load. Articular cartilage contact areas are clearly visualized, as well as their changing position and some surface deformation in the lateral tibial cartilage with loading in one subject.

Rotations and displacements of the joint during loading showed variations between subjects, however changes with loading were not significantly different from zero, with the exception of the anterior displacements (Table 1). Maximum flexion, abduction, and external rotations due to loading were 4.0, 1.1, and 4.6° respectively, while maximum med/lat and infra/sup translations were 0.9 and 1.6 mm. The axial load alone caused anterior displacement in 3 of the 5 five subjects, but on average, this displacement was not significantly different from zero. Anterior loads alone or in combination with axial loading caused greater anterior displacement than axial loads alone based on paired t-tests.

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Anterior Displacement (mm)</th>
<th>st. dev.</th>
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<tbody>
<tr>
<td>Axial 225 N</td>
<td>0.5±0.3±0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Axial 225 N / Anterior 107 N</td>
<td>2.2*</td>
<td>2.0</td>
</tr>
<tr>
<td>Anterior 107 N</td>
<td>2.0*</td>
<td>0.86</td>
</tr>
</tbody>
</table>

* significantly different from zero with 95% confidence # significantly different from other loading conditions, p<0.05

DISCUSSION:
These preliminary results are consistent with Beynon et al. indicating no anterior neutral shift with axial loading in the in vivo intact knee (1), however our sample size is small and smaller axial loads were applied. All anterior displacements identified were smaller than those measured by Torzilli et al., and no differences were found between displacements caused by anterior load alone and the combined loading condition (6). Our study suggests that the moderate (225 N) axial load applied was not sufficient to provide increased stability to the knee. With the MR images, it is now possible to visualize the associated secondary restraints such as the meniscus, collateral ligaments and joint capsule while loads are applied. Images of contacting articulating surfaces also provide insight on the role of joint conformity in stabilizing the joint or causing shifts. Investigations of the ACL-deficient knee are needed to further investigate the role of weightbearing in providing stability to the knee.

We assumed that the subjects are passive during our loading conditions, but some muscle activity may be present during loading. Although this challenge in the in vivo experiment creates some disadvantages relative to cadaveric studies, we believe our technique offers advantages for the study of live subjects. No radiation exposure is required, and three-dimensional motion may be assessed with greater reliability than radiographic approaches. The fast GRE sequences are adequate for bone motion tracking, but soft tissue visualization would be improved with routine GRE sequences, requiring approximately 15 minute scans. In three of the five subjects, one routine scan with 225 N axial load was also performed, and easily tolerated. Coupling this technique with finite element analysis could allow the investigation of changes in stress and strains in cartilage or other soft tissues during realistic loading conditions.

REFERENCES:

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