Validation of Anterior Cruciate Ligament Insertion Site Location and Area Determination Using High-Resolution 3D Isotropic Magnetic Resonance Imaging

Daisuke Araki, M.D., Ph.D.1,2, Eric Thorhauer1, Scott Tashman, Ph.D1, Freddie H. Fu, M.D.1.

1University of Pittsburgh, Pittsburgh, PA, USA, 2Kobe University Graduate School of Medicine, Kobe, Japan.

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Introduction: Reliable preoperative assessment of the knee joint is important for a successful anatomical placement of anterior cruciate ligament (ACL) reconstruction graft tunnels. Recently, Staebuli et al. and Tanaka et al. used MRI to investigate the ACL insertion and reported the ACL insertion sites in relation to the ACL bundles and surrounding anatomical landmarks [1, 2]. However, these previous reports were used clinical MRIs, these anatomical insertion sites obtained by MRI have not been validated and the accuracies of these measurements were still unclear. Advancements in magnetic resonance imaging (MRI) allow for the acquisition of high-resolution isotropic 3D sequences of the knee. The purpose of this study was to quantify the error in insertion site location and area determined from 3D isotropic MRI to native insertion site data obtained via accurate 3D laser scanning.

Methods: Twelve fresh-frozen ACL-intact cadaver knees (6 paired specimens) were used in this study (2 females and 4 males, age at death 62.0 ± 6.7 years). All specimens were obtained after approval of Office for Oversight of Anatomic Specimens in our institution. First, fiducial marker spheres filled with Radiance® multimodality fluid (Beekley, Bristol, CT) and attached to the heads of PEEK screws rigidly rigidly inserted into the specimens for dataset co-registration. Isotropic 3D DESS WS MRI sequences (Pixel size: 0.45 × 0.45 × 0.45 mm, TR: 16 ms) were collected for each knee and formatted into axial, coronal and sagittal planes (Siemens Trio 3T scanner). Specimen femurs and tibias were then disarticulated and the ACL insertion sites were carefully observed, dissected, and their boundaries marked with ink. Bone shafts were rigidly clamped into place while the ACL insertion boundaries and the co-registration spheres were digitized using a FARO Arm contact probe and laser scanner (FARO Corp., Lake Mary, FL). The ACL insertion sites and co-registration spheres were manually identified in MRI images using Materialise Mimics software (Leuven, Belgium). Co-registration was performed in Geomagic software (Geomagic, Durham, NC). These procedures are summarized in Figure 1. Anatomical coordinate systems were defined using laser scan data of the specimens' bones after removal of all soft tissues. ACL insertion site areas were calculated on planes fit to the medial wall of lateral condyle for femurs and the plateau for tibias. The percent overlapped area and the difference in centroid location of the insertion sites between MRI and laser scans were assessed. The anatomical direction of the difference in the centroid location between MRI and laser scans was also evaluated. Paired t-tests were used for assessing differences between the MRI and laser scan insertion site areas. Root mean square (RMS) differences were calculated for centroid locations. Significance levels were set at p < 0.05.

Results: Average co-registration error of the fiducial spheres was 0.6 ± 0.5 mm for femurs and 0.7 ± 0.2 mm for tibias, respectively. Femoral ACL insertion site area averaged 112.7 ± 17.9 mm² from MRI data and 109.7 ± 10.9 mm² from laser scan data. Tibial insertion site area was 134.7 ± 22.9 mm² from MRI and 135.2 ± 15.1 mm² from laser scan. There were no significant differences in area between MRI and laser scan (P = 0.345, P = 0.881). Percentage overlapped area of ACL insertion sites were 82.2 ± 10.2 % for femurs and 81.0 ± 9.0 % for tibias. The difference of the centroid location of ACL insertion sites between MRI and laser scan were 1.6 ± 1.1 mm for femurs and 2.2 ± 1.3 mm for tibias (Table 1). The average estimated centroid locations of ACL insertion sites in MRI were 0.6 ± 1.6 mm anteriorly and -0.3 ± 1.9 mm proximally for femur and -0.3 ± 1.1 mm anteriorly and 0.5 ± 1.5 mm proximally for femur a. The root mean square differences in the centroid of ACL insertion sites were 1.87 mm for femurs and 2.49 mm for tibias.

Discussion: The important findings of this study are that no significant differences were found in the area calculations and slight differences in the centroid locations of ACL insertion sites. Although average 80 % overlapped area and approximately 2 mm difference in the centroids were observed in both femoral and tibial ACL insertion sites, accurate detection of the ACL insertion sites were still challenging. Recent study by Mochizuki et al. reported that ACL insertions consisted of two functional fibers as fan-like extension and direct extensions [3]. Looking at the morphology of ACL insertion sites, the area described as fan-like extension becomes thick when the knee is extended. This may have affected the centroid location of ACL insertions in MRI. In addition, the probing procedure using laser scanner, co-registration process, misidentifying of meniscal root for ACL insertion in MRI, or the difference of MRI signals between living human and cadaver specimen may also have been increased the errors.
Despite these limitations, the current results suggest that anatomical ACL insertion sites can be identified using isotropic 3D MRIs with relatively high accuracy. As a future direction, if the side-to-side symmetry in ACL insertion sites is validated, the information of ACL insertion sites in contralateral knees can be used for preoperative planning for ACL reconstruction. Furthermore, the bone tunnel placement in ACL reconstruction can be reviewed by comparing with the centroids of tunnel apertures and native insertion sites obtained from the MRI of contralateral knees to perform anatomical ACL reconstruction.

**Significance:** 3D isotropic MRI scans could be used for accurate detection of ACL insertion site area and centroid location. This method allows for preoperative planning for anatomical reconstruction and to assess the anatomical tunnel placement by use of contralateral knees.

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**Table 1**

<table>
<thead>
<tr>
<th></th>
<th>Femur</th>
<th>Tibia</th>
</tr>
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<tbody>
<tr>
<td>% overlapped area</td>
<td>82.2 ±10.2</td>
<td>81.0 ±9.0</td>
</tr>
<tr>
<td>Centroid (mm)</td>
<td>1.6 ±1.1</td>
<td>2.2 ±1.3</td>
</tr>
<tr>
<td>A/P direction (mm)</td>
<td>-0.3 ±1.1</td>
<td>0.5 ±1.5</td>
</tr>
<tr>
<td>P/D direction (mm)</td>
<td>0.6 ±1.6</td>
<td>-0.3 ±1.9</td>
</tr>
<tr>
<td>Centroid RMS difference (mm)</td>
<td>0.6 ±0.5</td>
<td>0.7 ±0.2</td>
</tr>
</tbody>
</table>

(All values are presented as mean ± standard deviation.)

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