Three-dimensional In Vivo Motion Analysis of Anterior Cruciate Ligament Deficient Knees Using Single-plane Fluoroscopy: Comparison to Contralateral Uninjured Knees and Normal Control Knees

Takayuki Murayama, MD1, Takashi Sato, MD2, Satoshi Watanabe, MD2, Osamu Tanifuji, MD1, Koichi Kobayashi, PhD1, Tomoharu Mochizuki, MD1, Hiroshi Yamagiwa, MD1, Yoshio Koga, MD3, Go Omori, MD4, Naoto Endo, MD1.

1Niigata University, Niigata, Japan, 2Niigata Medical Center, Niigata, Japan, 3Hokuetsu Hospital, Shibata, Japan, 4Niigata University of Health and Welfare, Niigata, Japan.


Introduction: Anterior cruciate ligament (ACL) injury often leads to kinematic changes in the knee, resulting in symptoms of instability. Recently, 3 dimensional (3D)-2 dimensional (2D) registration techniques have been used to measure in vivo 3D dynamic kinematics of the ACL deficient (ACLD) knees. In these studies, however, using the 3D-2D registration, the dynamic motion of ACLD knees has simply been compared to that of the contralateral uninjured or normal control knees; no study has examined whether the motion of the contralateral uninjured knees is similar to that of normal subjects without knee disease or injury. It is controversial to simply use the contralateral uninjured knees as the normal control. We previously analyzed the in-vivo dynamic kinematics of normal knees via the 3D-2D registration, employing the geometric center axis (GCA) as an evaluation parameter [1]. We hypothesized that analysis of the kinematics of ACLD knees and their contralateral uninjured knees using the same method as that used in our previous study [1] would show that (1) the motion of the contralateral uninjured knees exhibits a pattern similar to that of the normal knees, (2) the motion of the ACLD knees exhibits a pattern different from those of the normal and contralateral uninjured knees. The purpose of this study was to evaluate the above hypotheses by analyzing the in vivo dynamic knee motion of unilateral ACLD subjects using the same method as in our previous study [1].

Methods: Twenty-six unilateral ACLD patients (11 male and 15 female patients) with a mean age of 21.8 years (range, 13-47 years) were enrolled in this study. The mean interval from injury to testing was 2.9 months (range, 1-6 months). The 3D digital models of the femur and tibia were reconstructed from the CT data and the anatomical coordinate systems were established. The GCA was defined as a segment connecting the centers of the spheres that represent the medial and lateral femoral posterior condyles (Fig. 1). Knee motion while subjects squatted from standing fully extended position to the maximum flexion was recorded using the flat panel detector. The 3D-2D registration was used to determine the 3D relative pose between the femur and tibia in the series of fluoroscopic images. The motion of the femur relative to the tibia was quantified as the movement of the GCA projected onto the tibial axial (x-y) plane. We determined the following parameters in the range 0 -120° of knee flexion: (1) changes in the angle of the GCA in the tibial axial plane (femoral rotation angle), (2) the anteroposterior (AP) locations, and (3) the ranges of AP translations of the medial and lateral ends of the GCA. A change in the angle of the GCA in the tibial axial plane was calculated as the rotation angle around the z-axis of the tibia. The AP locations of the medial and lateral ends of all projected GCAs were evaluated as the y values of the
tibial coordinate system. The range of AP translation of the medial (lateral) end of the GCA was defined as the distance in the AP direction from the most anterior to the most posterior point of the medial (lateral) end of the GCA through the entire trajectory of the end of the GCA while the subjects squatted in the range 0°-120° of knee flexion.

Data obtained was statistically analyzed by comparing the motion of the ACLD, contralateral uninjured, and normal (found in our previous study [1]) knees. When the data had a normal distribution, the one-way ANOVA with the Tukey post hoc test was used. When the data did not have a normal distribution, the Kruskal Wallis test was employed with the Bonferroni adjusted Mann-Whitney U test used as a post hoc test. The Data were considered to be statistically significant when p < 0.05.

**Results:** Changes in the angle of the GCA from 0° to 120° of flexion are shown in Table 1. No significant difference was found in the amount of femoral rotation angle among the ACLD, contralateral uninjured, and normal knees.

AP locations of the medial and lateral ends of the GCA are shown in Fig. 2, 3. At any flexion angles, the contralateral uninjured and normal knees showed no significant difference in the AP location of the medial and lateral ends of the GCA although there was a trend for the contralateral uninjured knees to be located more posteriorly. In contrast, comparing the ACLD and contralateral uninjured knees, while the AP location of the medial end of the GCA showed no significant difference at any flexion angles, that of the lateral end in the ACLD knees showed a significantly more posterior shift at 0° of flexion (p < 0.05). Compared to the normal knees, the AP locations of both the medial and lateral end of the GCA in the ACLD knees showed a significantly more posterior shift in early flexion phase (medial end at 0° : p < 0.01; medial end at 10°, 30°, 40°: p < 0.05; lateral end at 0°, 10°: p < 0.01; lateral end at 20°: p < 0.05).

The ranges of AP translations of the medial and lateral ends of the GCA are shown in Table 1. From 0° to 120° of flexion, the ACLD knees showed a significantly larger range of AP translation of the medial end of the GCA, compared to the contralateral uninjured and normal knees (to contralateral uninjured knees: p < 0.05, to normal knees: p < 0.01), while there was no significant difference between the contralateral uninjured and normal knees. Conversely, there was no significant difference in the range of the lateral end of the GCA among the ACLD, contralateral uninjured, and normal knees.

**Discussion:** The contralateral uninjured knees exhibited a motion pattern similar to the normal knees. Compared to the normal knees, however, there was a trend for both the medial and lateral femoral condyles in the contralateral uninjured knees to be located more posteriorly especially in the early flexion phase, although not significant. The lateral femoral condyle in the ACLD knees was located more posteriorly than in the contralateral uninjured knees at 0° of knee flexion. This posterior location of the lateral femoral condyle in the ACLD knees near full extension impaired screw-home movement. Both the medial and lateral femoral condyles of the ACLD knees were located significantly more posteriorly than those of the normal knees in the early flexion phase. The difference in the AP location of the femur between the ACLD and normal knees was greater than that between the ACLD and contralateral uninjured knees.

We found that the range of AP translation of the medial femoral condyle was larger in the ACLD knees than in the contralateral uninjured and normal knees. The larger range of AP translation of the medial femoral condyle in ACLD knees may be associated with a risk of secondary meniscus injury and degenerative change of knee joint.
Significance: Abnormal kinematics of ACLD knees might lead to the degenerative changes of the knee joint. The difference in the knee motion between ACLD and normal knees was greater than that between ACLD and contralateral uninjured knees.

Fig. 1 The medial and lateral posterior condyles were approximated as spheres. The geometric center axis (GCA) was defined as the segment connecting the centers of these two spheres.

Fig. 2. AP translation of the medial end of the GCA in the anterior cruciate ligament deficient (ACLD), contralateral uninjured, and normal [1] knees. (** p<0.01, * p <0.05 ACLD versus normal knees).
Table 1. A comparison between the unilateral ACLD and normal subjects (mean±SD)

<table>
<thead>
<tr>
<th></th>
<th>Femoral rotation angle (°)</th>
<th>Range of AP translation (medial) (mm)</th>
<th>Range of AP translation (lateral) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLD knees</td>
<td>19.5 ± 9.4</td>
<td>10.0 ± 2.8</td>
<td>9.7 ± 4.8</td>
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<tr>
<td>Contralateral uninjured knees</td>
<td>21.6 ± 10.5</td>
<td>7.7 ± 3.0</td>
<td>10.6 ± 5.3</td>
</tr>
<tr>
<td>Normal knees [1]</td>
<td>20.3 ± 5.8</td>
<td>7.3 ± 2.7</td>
<td>12.2 ± 3.9</td>
</tr>
</tbody>
</table>

*Fig. 3. AP translation of the lateral end of the GCA in the ACLD, contralateral uninjured, and normal [1] knees. (* p<0.05 ACLD versus contralateral uninjured knees; ** p<0.01, * p<0.05 ACLD versus normal knees)*

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