Fluoroscopic analysis of knee kinematics after total knee arthroplasty in osteoarthritis and rheumatoid arthritis

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SUMMARY

Unidirectional fluoroscopic three-dimensional knee kinematic analysis was performed. Eight knee joints that received total knee arthroplasty (TKA) with favorable postoperative courses were examined. They included 4 with osteoarthritis (OA) and 4 with rheumatoid arthritis (RA). The artificial joint used for all the subjects was High-Tech-Knee II, which was a flat-surface type and conserved the posterior cruciate ligament. The subjects were requested to go up and down one step 4 times continuously to take fluoroscopic images of the knee for kinematic analysis. Results were very similar between OA and RA. Contact points between the femoral and tibial components were on the posterior half of the tibial component. The medial condylar contact point was more posterior and showed a larger range of motion than the lateral contact point, resulting in a lateral pivot pattern of motion. A more detailed understanding of in vivo TKA kinematics is essential for developing better designs of artificial knee joints to.

Key words: total knee arthroplasty (TKA), kinematics, fluoroscopic analysis, osteoarthritis (OA), rheumatoid arthritis (RA).

1. Introduction

Artificial knee joints have been used clinically since the 1970's and are now in widespread use throughout the world. Long-term favorable clinical results over 10 years have been reported \cite{1-5}. Studies for further improving the clinical results, such as those on the improvement of metal materials and ultra-high-molecular-weight polyethylene, postoperative kinematic analysis, and fixation at the interface with bone, are now underway.

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Many studies have reported the kinematic analysis based on external markers or articular goniometers[6-12]. However, potential errors caused by the movement of soft tissues including muscles and skin limit the useful resolution of these techniques.

To avoid the effects of such soft tissues, a fluoroscopy-based three-dimensional kinematic analysis was performed for the femoral and tibial components after total knee arthroplasty (TKA).

II. Material and Methods

The kinematic analysis was performed with the unidirectional fluoroscopy by Banks et al [13]. Unidirectional fluoroscopic images obtained for the knee joint were inputted to a computer. The obtained images had different distortion and enlargement rates between the center and edge because the image intensifier of the fluoroscopic device was not flat and had its own curvature. To convert the images to accurate flat ones, 2 corrections were made. First, the distortion of the images was corrected by taking fluoroscopic images of metal markers set at the nodal points of an accurate grid. Second, the enlargement rates at the center and edge were corrected by taking the fluoroscopic images of metal markers radially arranged at equal intervals. These corrections allowed the conversion of the original images of artificial knee joints to accurate flat images (Fig.1). Then, the accurate images were compared on the computer with the images of the femoral and tibial components from the data of the computer-aided design models of artificial knee joints. Based on these processes, the position and direction of each component were three-dimensionally determined.

Eight knee joints that received TKA with favorable postoperative courses were examined. They included 4 with osteoarthritis (OA) and 4 with rheumatoid arthritis (RA). The mean age of the subjects was 63 years (range: 55 to 71 years). The mean period between surgery and postoperative kinematic analysis was 8.1 months (range: 6 to 16 months). The mean

Fig. 1 Correction from perspective silhouette to accurate flat image.
   a) Perspective silhouette.
   b) Accurate flat image after correction.
Japan orthopaedic association score was 80 (range: 75 to 85) for the 4 joints with OA and 92 (range: 91 to 95) for the 4 joints with RA. The postoperative mean range of motion of the joints was 114° (range: 100° to 120°). All of these values indicated clinically favorable results. The artificial joint used for all the subjects was High-Tech-Knee II (Nakashima Medical, Okayama, Japan), which was a flat-surface type and conserved the posterior cruciate ligament. Surgery was performed through the medial para-patellar approach with lateral release. Posterior cruciate ligament (PCL) was recessed at the level of proximal tibial cutting line without retaining insertion of PCL. The subjects were requested to go up and down one step 4 times continuously to take fluoroscopic images of the knee for kinematic analysis.

III. Results

The contact point of the femoral and tibial components was averaged for all the trials of all the subjects by flexion angles, and the resultant mean values are summarized for the medial and lateral sides in Figure 2. The antero-posterior central line on the tibial component was considered zero (0), with the anterior and posterior points being considered positive and negative, respectively. The contact points were generally posterior to the central line on the tibial component for both medial and lateral sides in all the subjects during the step-up and step-down movements. When the knee was flexed from the extended position, the contact point initially moved posteriorly (rolling), but then moved anteriorly (sliding) for both medial and lateral sides (Fig.2).

The mean antero-posterior contact point was \(-12.0 \pm 2.7\) mm on the medial side and \(-9.3 \pm 2.6\) mm on the lateral side for the joints with OA; \(-9.0 \pm 3.9\) mm and \(-5.3 \pm 3.2\) mm for those with RA; and \(-10.4 \pm 3.7\) and \(-7.2 \pm 3.6\) mm for all the joints (Table 1, Fig.3).

The most anterior contact point (MAC) and most posterior contact point (MPC) were located for each trial. The mean MAC was \(-7.1 \pm 1.9\) mm on the medial side and \(-6.4 \pm 2.9\) mm on the lateral side for OA; \(-2.9 \pm 3.6\) mm and \(-0.6 \pm 4.0\) mm for RA; and \(-5.1 \pm 3.6\) mm and \(-3.6 \pm 4.5\) mm for all the joints. The mean MPC was \(-14.7 \pm 2.0\) mm on the medial side and \(-12.0 \pm 2.5\) mm on the lateral side for

![Fig. 2 Antero-posterior contact point of the femoral and tibial components in all the joints grouped by flexion angles of the knee. The antero-posterior central line on the tibial component is considered zero, with the anterior and posterior points being considered positive and negative.](image_url)
Table 1 Antero-posterior contact point of the femoral and tibial components. The antero-posterior central line on the tibial component is considered zero, with the anterior and posterior points being considered positive and negative.

<table>
<thead>
<tr>
<th></th>
<th>med A/P (mm)</th>
<th>lat A/P (mm)</th>
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<tbody>
<tr>
<td>OA</td>
<td>-12.0 ± 2.7</td>
<td>-9.3 ± 2.6</td>
</tr>
<tr>
<td>RA</td>
<td>-9.0 ± 3.9</td>
<td>-5.3 ± 3.2</td>
</tr>
<tr>
<td>All</td>
<td>-10.4 ± 3.7</td>
<td>-7.2 ± 3.6</td>
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Values are mean ± S.D.

Fig. 3 Antero-posterior contact point figured on the tibial component in OA and RA and all the joints.

OA; -13.0 ± 2.8 mm and -9.0 ± 2.6 mm for RA; and -13.9 ± 2.5 mm and -10.6 ± 3.0 mm for all the joints (Table 2 and Fig. 4 and 5). MAC was not significantly different between the medial and lateral sides, while MPC was significantly different between the medial and lateral sides for OA, RA, and all the joints (Mann-Whitney U-test).

The antero-posterior movement range of the contact points (contact range) was not significantly different between the medial and lateral sides for both OA and RA, although the medial contact range tended to be larger (Table 3-a). The mean medial contact range of all the joints was 8.8 ± 3.9 mm, which was significantly larger than the mean lateral contact range at

Table 2 Most anterior and posterior contact point. In each group the mean medial MPC is smaller than the mean lateral MPC significantly (Mann-Whitney U-test).

<table>
<thead>
<tr>
<th></th>
<th>medial MAC (mm)</th>
<th>lateral MAC (mm)</th>
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<tr>
<td>OA</td>
<td>-7.1 ± 1.9</td>
<td>-6.4 ± 2.9</td>
</tr>
<tr>
<td>RA</td>
<td>-2.9 ± 3.6</td>
<td>-0.6 ± 4.0</td>
</tr>
<tr>
<td>All</td>
<td>-5.1 ± 3.6</td>
<td>-3.6 ± 4.5</td>
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<table>
<thead>
<tr>
<th></th>
<th>medial MPC (mm)</th>
<th>lateral MPC (mm)</th>
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<tbody>
<tr>
<td>OA</td>
<td>-14.7 ± 2.0</td>
<td>-12.0 ± 2.5</td>
</tr>
<tr>
<td>RA</td>
<td>-13.0 ± 2.8</td>
<td>-9.0 ± 2.6</td>
</tr>
<tr>
<td>All</td>
<td>-13.9 ± 2.5</td>
<td>-10.6 ± 3.0</td>
</tr>
</tbody>
</table>

Values are mean ± S.D. 
MAC, most anterior contact point 
MPC, most posterior contact point

Fig. 4 Most anterior contact point (MAC) figured on the tibial component in OA and RA and all the joints.

Fig. 5 Most posterior contact point (MPC) figured on the tibial component in OA and RA and all the joints.
Table 3-a  Antero-posterior movement range of contact points (contact range). The mean medial contact range of all the joints is significantly larger than the mean lateral contact range (Mann-Whitney U-test).

<table>
<thead>
<tr>
<th></th>
<th>medial contact range (mm)</th>
<th>lateral contact range (mm)</th>
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<tbody>
<tr>
<td>OA</td>
<td>7.6 ± 3.4</td>
<td>5.6 ± 2.5</td>
</tr>
<tr>
<td>RA</td>
<td>10.1 ± 4.1</td>
<td>8.3 ± 2.5</td>
</tr>
<tr>
<td>All</td>
<td>8.8 ± 3.9</td>
<td>6.9 ± 2.9</td>
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Values are mean ± S.D.

Table 3-b Results of the contact range in previous reports. The mean medial contact range is larger than the mean lateral contact range in both results.

<table>
<thead>
<tr>
<th></th>
<th>medial contact range (mm)</th>
<th>lateral contact range (mm)</th>
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<tbody>
<tr>
<td>Banks</td>
<td>8.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Stiehl</td>
<td>5.4</td>
<td>1.7</td>
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Values are mean 6.9 ± 2.9 mm (Mann-Whitney U-test).

These results show that there was no difference in MAC between the medial and lateral side; that MPC on the medial side was located more posteriorly than that on the lateral side; and that the contact range was larger on the medial side. The results suggest that there may be a rotational movement between the femoral and tibial components during the step-up and step-down movements.

When the angle of the external rotation of the tibial component in relation to the femoral component was considered positive and the angle of rotation in all the joints was grouped by the flexion angles of the knee, the tibial component rotated externally and showed a screw home movement as the knee joint was extended from the bend at about 40°. The external rotation of the tibial component was markedly reduced when the knee joint was fully extended. It was also shown that the tibial component rotated internally as the knee joint was flexed from the bend at about 50° (Fig. 6). The mean range of rotation of the tibial component in relation to the femoral component was 5.8 ± 3.7° for all the knees, 5.6 ± 3.9° for OA, and 6.1 ± 3.5° for RA, with no significant difference between OA and RA (Table 4).

When the relation of the position of the contact point between the femoral and tibial components with rotational movements was

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Fig. 6 Rotation of the tibial component in all the joints grouped by flexion angles of the knee. The angle of the external rotation of the tibial component in relation to the femoral component is considered positive.

Table 4  Range of rotation of the tibial component in relation to the femoral component (maximum external rotation-maximum internal rotation).

<table>
<thead>
<tr>
<th></th>
<th>range of rotation</th>
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<tbody>
<tr>
<td>OA</td>
<td>5.6 ± 3.9 (degree)</td>
</tr>
<tr>
<td>RA</td>
<td>6.1 ± 3.5</td>
</tr>
<tr>
<td>All</td>
<td>5.8 ± 3.7</td>
</tr>
</tbody>
</table>

Values are mean ± S.D.
examined at the flexion angles of about 0, 30, and 60°, the lateral contact point moved only slightly, while the medial contact point showed marked roll-back and anterior sliding movements, resulting in a lateral pivot motion as a whole (Fig. 7).

IV. Discussion

The three-dimensional kinematic analysis of the knee after TKA has been performed by attaching markers or goniometers on the knee. However, these methods cannot eliminate the effect of soft tissue and the degree of the effect remains unknown. The present method with fluoroscopy is excellent in that it can directly capture the movement of each component. Several studies have recently reported the in vivo kinematic analysis based on the method [13-21]. Banks et al. have reported that the standard error of this analysis was as large as 8.2 mm for the movement along the Z axis that was perpendicular to the image plane, or for the far-and-near movement from the image plane, while that for the movement along the X or Y axis, or for the antero-posterior or up-and-down movement of the knee joint, was less than 1 mm. The standard error of rotation was less than 2° for the axes of X, Y, and Z (Fig. 8).

Table 5. The present analysis showed the following common findings to OA and RA: (1) there was no difference in MAC between the medial and lateral sides; (2) medial MPC was significantly more posteriorly positioned than lateral MPC; (3) the medial contact range was larger than the lateral contact range; and (4) there was no
difference in the range of rotation. These results show that the joints affected by OA and RA probably moved in the same way after TKA. Although RA induces inflammatory change over the whole joint and is different from OA in that it affects the soft tissue components, such as the ligaments, total knee arthroplasty may give the knee joints affected with RA the same kinematics as those with OA. However, as demonstrated by the wider medial and lateral contact ranges, the knee joints affected by RA tend to be less stable than those affected by OA during movement.

Banks et al. [15] assigned patients with OA to 3 groups (Group 1: flat tibial insert and retained insertion of PCL, Group 2: flat tibial insert and recessed PCL without retaining insertion, and Group 3: conformal tibial insert and sacrificed PCL) and instructed them to go up and down 1 step to evaluate the in vivo three-dimensional kinematics of the knee using fluoroscopy. The result showed the 3 treatments produced different kinematics modes. Stiehl et al. [20] instructed patients treated with TKA with flat tibial insert and PCL retained (primary diseases not described) to deeply bend the knees to analyze the kinematics of the knees with fluoroscopy. Based on the results, they reported that the lateral pivot with medial anterior translation, that is, abnormal positive screw home motion occurred as they bent the knees.

The patients in Group 2 of Banks et al., those analyzed by Stiehl et al., and our patients were considered to be analyzed in the same manner because all of them were treated with flat surface and PCL preserved and instructed to bend the knees under loaded condition. The results of the 3 groups were very similar as follows:

1) The contact point of the femoral and tibial components is located posteriorly to the antero-posterior center of the tibial component.

2) The medial contact range/lateral contact range of the 3 groups was 8.2mm/6.1mm, 5.4mm/1.7mm, and 8.8mm/6.9mm (OA 7.6mm/5.6mm and RA 10.1mm/8.3mm), respectively (Table 3-b). The medial contact range was larger than the lateral contact range in all the groups. This indicates that the knee movement was generally a lateral pivot motion.

3) The range of rotation of the 3 groups was 6.5°, 4.7°, and 5.8° (OA 5.6° and RA 6.1°), respectively. This indicates that the range of rotation was close to each other in the 3 groups.

The study of Stiehl et al. [20] showed the positive screw home motion with medial anterior translation (that is, lateral pivot) when the knee was bent from 0 to 60°. In contrast, our results showed the negative screw home motion with medial posterior translation (lateral pivot) when the knee was bent from 0 to 30° and the positive screw home motion with medial anterior translation (lateral pivot) when the knee was bent from 30 to 60°. These results indicate that the detail kinematic mode of the 2 groups was different. Banks et al. [15] described that the kinematics of the knee after posterior cruciate retaining TKA was very different between when bony insertion of PCL was retained and when bony insertion of PCL was not retained. Therefore, the different screw home motions between the Stiehl's and our results probably result from inconsistent factors between the studies, including the differences in detail surgical techniques, such as the extent of recessing PCL, and the differences in the shape of the femoral components.

Various designs of artificial knee joints have been clinically introduced. Recently, many of them have adopted conformed inserts to reduce the stress to the tibial insert, although the degree of conformity has been various. When
the shape of a confirmed insert does not fit the
kinematics of the knee after TKA, excessive
stress is eventually applied to the components,
resulting in the destruction of the polyethylene
insert. It is therefore essential for developing
better designs of artificial knee joints to under-
stand more detailed in vivo kinematics of the
knee after TKA.

要 旨
【目的】従来膝関節の動態解析は、筋肉・皮膚など軟
部組織を介して体表面上に関節角度計や表面マーカー
を設置し行われてきた。これら軟部組織の影響を受け
ないX線透视を用いた人工膝関節置換術（TKA）後の
三次元動態解析を行った。
【方法】TKA術後一方向X線透视により得られる透視
画像をコンピューターに取り込む。得られた画像を透
視装具解釈の解析と合わせ、これをCADモデル
データーにより得られる像とコンピューター上で比較し、
各コンポーネントの位置・動きを三次元的に決定した。
術後経過が良好な変形性関節症（OA）4膝、慢性関節
像と比較（RA）4膝を対象とし、一段の階段昇降を透
視下に4回連続で行った。
【結果】Contact pointは主に脛骨インサートの中心
線より前方に存在していた。Most posterior contact
pointは内側はOA、RA また全症例において有意に
前方に存在していた。Contact rangeはOA、RAと
も内側の方が大きい傾向にあり、全症例では内側の方
が有意に大きかった。膝関節の屈伸に伴う脛骨は回旋
し、screw home movement・lateral pivot motion
を示した。
【考察】X線透视を用いた本法は、各コンポーネント
の運動を直接とられることができる優れた方法である。
今回の解析では、RAは関節全体に変性があるにもかか
わず術後の運動はOAと類似していた。現在、多
くの人工膝関節が臨床応用されている。その変形が術
後の運動様式に合わなければ、インプラントの破壊へ
つながるものと思われる。TKA術後のより詳細な動態
解析が、より優れたデザイン開発に不可欠であると考え
る。

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