Analysis of Normal and Replaced Knee Kinematics in an Isometric Extension Model

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Introduction

An open-chain model was used to investigate the kinematics during isometric extension between normal knees and knees replaced with a tricompartmental prosthesis.

Methods

Ten cadaver legs were skeletonized while preserving the knee joint capsule, quadriceps and hamstring tendons. CT scans of the extremity were converted to CAD models that precisely related the bone surfaces to radio-opaque motion analysis markers. The limbs were mounted in a custom open-chain extremity rig [1]. Tibial motion was produced by a linear actuator attached to the quadriceps tendon in the direction of the vector addition of the absent quadriceps muscles. Tendon force was measured with an in-line force transducer and recorded at 30 Hz during the motion. Three-dimensional kinematic data of the isometric extension motion of the knee were recorded at 30 Hz using a motion capture camera system and combined with CAD models of the extremity to evaluate joint kinematics through virtual animations, contact points, and kinematic profiles. After collecting data on normal knee kinematics, each specimen underwent total knee replacement with commercially available implants. Knee kinematics were determined from the motion capture data and the captured motion was imposed on the virtual model. The femoral anatomic axis was defined as a line from the center of the femoral head to the posterior cruciate ligament (PCL) femoral insertion point [2]. The tibial anatomic axis was defined as a line from the center of the line connecting the proximal tibial prominences to the center of the distal tibial articular surface [2]. The femoral internal/external (IE) rotation reference was a line connecting the peaks of the medial and lateral epicondyles [2]. The tibial IE rotation reference was a line defined by the anterior boundaries of the articular surfaces [3]. IE rotation angle was defined as the angle between these two reference lines, on a plane perpendicular to the tibial axis. Contact points between the femur and tibia, or corresponding components for the implanted knee, were determined in 30° increments between full extension and 120° flexion [4]. Animations of the virtual CAD models were created for visualization of the motion data.

Results

Tibio-femoral contact points for the normal knee indicate stable behavior on the medial compartment and progressive posterior motion of contact on the lateral side with increasing flexion. The normal knees demonstrated anterior contact on both the medial and lateral sides at full extension (0°). Within the first 30° of flexion, the contact point moves backwards on both medial and lateral sides of the joint, but markedly more so on the lateral. From then on, the contact point stays stable in the mid portion of the medial tibial plateau and more posterior on the lateral demonstrating medial pivoting kinematics. The replaced knee does not demonstrate the “screw-home” from 0°-30° but does demonstrate a stable medial contact point in the mid portion of the tibial plateau and gradual posterior movement of the contact point on the lateral side through 120°, indicating medial pivoting kinematics similar to the normal. These patterns were virtually identical across all specimens. Contact point translation data after knee replacement was consistent with the behavior of the normal knee. The anterior-posterior translation of each condyle for each specimen was normalized and averaged (Table 1). The replaced knee demonstrated equal or smaller displacement values in all but one category (lateral deep flexion) and maintained similar profiles in all flexion ranges. Contact points from a representative specimen are shown in Figure 1. These results indicate that the replaced knee is stable medially throughout the range of motion with controlled lateral translation.

The contact point AP position was compared at discreet flexion angles between normal and replaced knees. On the medial side, from 0°-110°, there was no statistical significant difference between the two cases with the p-values ranging from 0.45 to 0.79. However at 115° of flexion, the p-value was 0.04 indicating a statistical difference between the normal and replaced knees. The lateral condylar comparison yielded three flexion angles with a statistical difference, 60°, 105°, and 115° with p-values of 0.05, 0.03, and 0.01 respectively. The mobility of the normal lateral compartment and the more constrained motion path of the replaced component are a factor of these differences.

Table 1: Condylar Contact Point AP Translation (mm)

<table>
<thead>
<tr>
<th>Flexion Angle</th>
<th>Normal - Medial</th>
<th>Normal - Lateral</th>
<th>Replaced - Medial</th>
<th>Replaced - Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°-30°</td>
<td>3.0</td>
<td>1.0</td>
<td>0.0</td>
<td>2.8</td>
</tr>
<tr>
<td>30°-90°</td>
<td>1.0</td>
<td>2.6</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>90°-120°</td>
<td>3.5</td>
<td>4.1</td>
<td>0.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Total</td>
<td>7.5</td>
<td>21.7</td>
<td>2.1</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Figure 1: Contact Point Profiles for Normal and Replaced Knees

Kinematic profiles of internal-external rotation and adduction-abduction for normal knees were consistent in shape among all specimens. Replaced knee kinematic profiles varied from normal but were consistent across specimens.

The peak quadriceps tendon load for all specimens occurred at 65° with a decrease as the leg progressed to full extension. Tendon load of the implanted knee reached a maximum at 65° which then remained nearly constant through 15°. Tendon loads at 65° are within 10% of the normal knee loads (-4.5 ± 5.6) with two of the three specimens having greater than 10% decreases in tendon load.

Discussion and Conclusion

The normal knee kinematics appear to be driven by the bone geometry and the physical constraints of the soft tissues. The replaced knee kinematics are dependent mostly on the designed geometry of the implants since both cruciate ligaments and cartilage are absent from these trials. The total knee prosthesis implanted was designed as a ball-in-socket on the medial side with a “ball-in-arcuate groove” on the lateral side. This design was intended to mimic the stable medial side of the normal knee while allowing the lateral side to rotate around it. In this open chain model, both normal and replaced knees indicate a stable medial side and free motion on the lateral side, demonstrating medial pivoting kinematics. The replaced knees also closely approximate the surface kinematics of the normal knees.

Variation in kinematic profiles between the normal and replaced knees are partially attributed to surgical alignment correction.

The quadriceps load necessary to move the knee at the same rate through the same range of motion were similar for the replaced knee compared to the normal knee exceeding the normal load by a maximum of 2%.

References