QUANTIFICATION OF SOFT TISSUE BALANCE IN TOTAL KNEE ARTHROPLASTY USING FINITE ELEMENT ANALYSIS

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SUMMARY
Unbalanced contact force on tibial component has been considered as a factor leading to the knee instability. The soft tissue balance has been examined because unequal soft tissue tension may cause the medial collateral ligament contracture in varus knee. In this study, we performed the X-ray based patient-specific contact analysis using several existing image matching technologies and finite element method to examine whether good radiographic alignment can provide well balanced medial and lateral contact forces, and to investigate how much of soft tissue balance would be necessary for the specific patient case. The results indicated that good radiographic alignment cannot always provide well balanced medial and lateral contact forces, and investigate adequate soft tissue balance in total knee arthroplasty to achieve well balanced contact force distribution for the specific case using patient-specific biomechanical modeling technology and finite element analysis technique. By combining the patient-specific ligament stiffness properties, the techniques presented in this study could be useful to provide the patient-specific planning to get optimal outcomes in TKA.

INTRODUCTION
Unbalanced contact force during load-bearing on tibial component has been considered as a factor leading to loosening of the implant and increased wear of bearing surface [1]. The contact force loading has been known to be dependent on body weight, alignment of extremity, contact area and soft tissue balance [1]. Hence, the achievement of good mechanical alignment has first been studied because correction of mechanical mal-alignment would produce equal loading on medial and lateral compartments [2]. However, clinical reports and experiences have shown that good alignment could not guarantee the successful clinical outcomes [3]. The soft tissue balance has been then examined because unequal soft tissue tension may cause the medial collateral ligament contracture in varus knee [1,3]. Although manual measurement of soft tissue balance has been advocated using balancers to equalize the medial and lateral gaps, the margin of error is high.

The recent technologies for patient-specific biomechanical modeling, image matching, and finite element analysis can help to achieve the clinically feasible quantitative pre-operative planning for soft tissue balance. In this study, we performed the X-ray based patient-specific contact analysis using several existing image matching technologies and finite element method to examine whether good radiographic alignment can provide well balanced medial and lateral contact forces, and to investigate how much of soft tissue balance would be necessary for the specific patient case. We evaluate the effects of the alignment and the pre-tension of medial cruciate ligament (MCL) and lateral cruciate ligament (LCL) on contact force distribution after TKA.

METHODS
Pre- and post-operative radiographic images of five patients’ lower limbs were taken in standing posture for the AP and sagittal planes. To obtain patient specific 3D models of femur and tibia, template model of the bones was created by 3D scan of saw bones. The patient-specific models of femur and tibia were then developed by free-form deformation method using the template model and pre-operative radiographic images of the patients [4]. The 3D models of the implants used in TKA surgery for five patients were reconstructed by 3D scan of the implants. The developed 3D models of bones and implants were aligned by 2D-3D matching method using post-operative images [5]. The angles, mechanical lateral distal femoral angle (mLDFA) and medial proximal tibial angle (MPTA), were then measured to evaluate the femoral and tibial alignments.

The finite element models of the lower extremities of five patients were then developed from the aligned 3D model of bones and implants using FEMAP® (Figure 1). Three bundles of MCL and LCL were attached on the finite element model, which represent the nonlinear stress-strain relations [6]. The body weight of each patient was applied on the femoral head center along the line from the hip joint center to the ankle joint center to calculate the medial and lateral contact forces. Equal ligament pretension of 100 N in both MCL and LCL were assumed. The medial and lateral contact force distributions between the femoral component and the tibial insert were estimated by using finite element analysis software ABAQUS/Standard®.

We selected a patient whose contact force distribution was the most unbalanced. The PCSA of the ligaments on the side, in which the higher contact force was assessed, was reduced by
10% and 20% for the soft tissue release to describe the soft tissue release by decreasing the ligament’s pretension. In addition, the thickness of the tibial insert was increased by 1 mm, 2 mm, and 3 mm to simulate the ligament tightening. Medial and lateral contact force distribution between the femoral component and the tibial insert in various soft tissue release and ligament tightening was evaluated by the finite element analysis.

RESULTS AND DISCUSSION
The mLFDA and MPTA in full-leg standing radiography were 90.6° ± 1.5° and 90.0° ± 0.5°, respectively. The average contact force distributions of medial and lateral compartments were 55.8% ± 4.3% and 44.2% ± 4.3% respectively. Only Patient 2 had well balanced contact force distribution (50%:50%) while the others had unbalanced distributions. Patient 3 had the most unbalanced distribution (61%:39%). In the case of Patient 3, the contact force distribution was improved when reducing PCSA of MCL and when the thickness of tibial insert was increased with the soft tissue release by 20%, medial contact force percentage decreased to 50%.

The results indicated that the contact force distributions for 4 patients out of 5 patients were not balanced equally between the medial and the lateral compartments even though the alignment angles were within clinically acceptable range for all the cases. This means that good radiographic alignment does not always guarantee balanced contact force distribution as in the literature [3]. To obtain good contact force balance, intra-operative soft tissue tensioning must be evaluated and realignment of the implant or adequate soft tissue releasing must be followed. In the conventional gap balancing technique for TKA surgery, the femoral component is parallel to the resected proximal tibia with equal pretensions of the collateral ligaments. Then, it was shown that the medial and lateral contact forces in standing posture are not same. The medial contact force distribution was reduced by only 3% with 3 mm increase of the ligament tightening. However, combined 3 mm of ligament tightening with 10% to 20% of soft tissue release balanced the force distribution to 54%-46% and 50%-50%, respectively. The results of this study suggested that adequate soft tissue balance could pre-operatively balance the contact force distribution for patient-specific optimal TKA surgery.

CONCLUSIONS
We examined that good radiographic alignment cannot always provide well balanced medial and lateral contact forces, and investigate adequate soft tissue balance in total knee arthroplasty to achieve well balanced contact force distribution for the specific case using patient-specific biomechanical modeling technology and finite element analysis technique. By combining the patient-specific ligament stiffness properties, the techniques in this study could be useful to provide the patient-specific planning to get optimal outcomes in TKA.

Table 1: Medial and lateral contact force distribution on tibial insert under various soft-tissue release and ligament tightening
(M: Medial, L: Lateral)

<table>
<thead>
<tr>
<th>No release</th>
<th>10% MCL release</th>
<th>20% MCL release</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Initial thickness of tibial insert</td>
<td>61%</td>
<td>39%</td>
</tr>
<tr>
<td>1 mm increase of thickness</td>
<td>58%</td>
<td>42%</td>
</tr>
<tr>
<td>2 mm increase of thickness</td>
<td>58%</td>
<td>42%</td>
</tr>
<tr>
<td>3 mm increase of thickness</td>
<td>58%</td>
<td>42%</td>
</tr>
</tbody>
</table>

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REFERENCES