Clinical Outcomes after Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction: Comparison of Extreme Knee Hyperextension and Normal to Mild Knee Hyperextension

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**Purpose:** To compare the postoperative outcome after anatomic double-bundle anterior cruciate ligament reconstruction (ACLR) between extreme knee hyperextension and normal to mild knee hyperextension. **Methods:** For 100 patients who underwent anatomic double-bundle ACLR using semitendinosus tendon, we evaluated the side-to-side difference (SSD) in anterior tibial translation, measured on stress radiographs, and rotational stability, assessed by pivot-shift test, 2 years after surgery. Loss of extension (LOE) was evaluated on lateral radiographs of both knees in full extension, and graft integrity was assessed during second-look arthroscopy 1 to 2 years after surgery. In accordance with the Beighton and Honan criteria, patients with an extension angle of contralateral uninjured knee of $\leq 10^\circ$ comprised the group with $10^\circ$ or less hyperextension (N group) and those with an extension angle of $>10^\circ$ comprised the group with more than $10^\circ$ hyperextension (H group). Postoperative results were compared between these groups. **Results:** Mean extension angles in N and H groups were $5.8 \pm 2.9^\circ$ and $14.7 \pm 3.0^\circ$, respectively. The mean SSD in anterior translation were $2.2 \pm 2.9$ for the N group and $2.8 \pm 2.9$ mm for the H group, with no significant difference. The positive ratios on the pivot-shift test were not significantly different between the groups. Mean LOE in the N and H groups were $-0.7 \pm 3.7^\circ$ and $1.3 \pm 3.3^\circ$, respectively, with a significant difference ($P = 0.007$). During second-look arthroscopy, 6 of 58 knees in the N group and 13 of 42 knees in the H group had superficial graft laceration of the anteromedial bundle graft, with a significant difference ($P = 0.01$). **Conclusion:** Anatomic double-bundle ACLR for extreme knee hyperextension may obtain the same postoperative anterior and rotational stability as for normal to mild knee hyperextension. However, it increased superficial graft laceration. **Level of Evidence:** III, retrospective comparative study.
INTRODUCTION

Numerous factors, such as graft type, surgical technique, postoperative rehabilitation, and gender, have been reported to be involved in the outcome of anterior cruciate ligament (ACL) reconstruction. General joint laxity has also been recognized to be a risk factor affecting postoperative outcome. Recently, however, it has been reported that knee hyperextension rather than general joint laxity is the risk factor that best predicts poor results for ACL reconstruction. A negative effect of knee hyperextension on ACL reconstruction is that ACL graft roof impingement might be increased, which results in graft deterioration, re-rupture, and postoperative loss of extension (LOE).

Several authors have reported that anatomic ACL reconstruction in which the tunnels are placed in the native femoral and tibial footprint can restore knee kinematics close to that of normal knees and provide better knee stability. In addition, anatomic ACL reconstruction eliminated the concern about roof impingement compared with traditional ACL reconstruction because the femoral tunnel is created at a lower position than in traditional ACL reconstruction. Iriuchishima et al. showed no significant difference in roof impingement pressure between intact ACL and anatomic ACL reconstruction in a cadaveric study, even if the tibial tunnel is placed in an anatomic anterior portion of the ACL insertion site. All intact ACL make contact with the intercondylar roof and it may be that a certain degree of roof impingement is physiological. However, the amount of impingement is correlated with the capacity for passive hyperextension, and it is expected that the adverse effect of roof impingement after anatomic ACL reconstruction for knee hyperextension is greater than that in normal knees.

The purpose of our study was to compare the postoperative outcome after anatomic double-bundle ACL reconstruction between extreme knee hyperextension and normal to mild knee hyperextension. Our hypothesis was that anatomic double-bundle ACL reconstruction for extreme knee hyperextension can obtain the same knee stability as for normal to mild knee...
hyperextension and does not result in an adverse effect of roof impingement because anatomic ACL reconstruction restores physiological roof impingement.

MATERIALS AND METHODS

Between August 2008 and July 2012, 167 patients underwent primary ACL reconstruction with semitendinosus tendon at our institute. Patients who had unilateral ACL injury and underwent anatomic double-bundle reconstruction were included in our study. Patients were excluded if they had single-bundle reconstruction, bilateral ACL injury, multiple ligamentous injuries, fractures around the knee, or a knee with osteoarthritic change on a radiograph before surgery. Patients who simultaneously underwent meniscal repair or partial meniscectomy were not excluded because the postoperative protocol was not altered with or without it. This study was approved by our institutional review board.

Surgical Technique

All patients underwent arthroscopic ACL reconstruction using semitendinosus tendon autograft. The tendon was cut in half to create both an anteromedial bundle (AMB) graft and a posterolateral bundle (PLB) graft; each tendon was doubled. An EndoButton CL (Smith & Nephew, Andover, MA, USA) was attached at the looped end of each graft, and a Telos artificial ligament (Telos, Marburg, Germany) was sutured with the free end of each graft via a gloved suture technique. The graft diameters of the AMB and PLB were 5 to 7 mm and 5 to 6 mm, respectively.

After the ACL remnant was resected around the femoral footprint, we created femoral tunnels through an accessory anteromedial portal. While keeping the knee at maximum flexion, we inserted a 2.4-mm Kirschner wire at the center of the AMB footprint, which is located anterior to the posterior cartilage margin of the lateral femoral condyle and behind the lateral intercondylar ridge at 90° knee flexion. The wire was overdrilled with a 4.5-mm cannulated
drill, and then the length of the tunnel was measured with a depth gauge. Then, a femoral socket was reamed with a cannulated drill matched to the diameter of the AMB graft. Similarly, we created a femoral tunnel for the PLB graft, while keeping the knee at maximum flexion, at the center of the PLB footprint, which is located at the most peripheral position of the lateral femoral condyle and behind the ridge at 90° knee flexion (Fig. 1A). We did not perform a notchplasty in any knee.

Next, we created tibial tunnels using an ACL drill guide. A tunnel for the AMB graft was created at the anteromedial position of the ACL footprint. A tunnel for the PLB graft was created anterior to the intertubercular ridge between the medial and lateral tibial intercondylar tubercles (Fig. 1B). So as not to create an AMB tunnel more anterior to the anatomic footprint, we checked the guide wire position in near extension of the knee. In near extension, the transverse ligament moves forward, making the anterior edge of the tibial footprint visible.

The grafts were passed through each tunnel, the femoral side was secured by flipping the EndoButton, and tibial fixation was accomplished with 2 spiked staples (Ai-Medic, Tokyo, Japan). Because biomechanical study has shown that average strains in the two bundles were equal at 15° knee flexion, we tensioned each bundle at 30 N with the knee at 15° flexion, using a ligament tensioner.

**Postoperative Rehabilitation**

The postoperative rehabilitation protocol was the same for all patients. Partial weight-bearing was started 1 week after surgery, progressing to full weight-bearing at 3 weeks. Range-of-motion exercises were initiated at 1 week after surgery, and a full range of motion was allowed at 3 weeks. Jogging was started at 3 months. We allowed jumping-and-cutting exercises, as used in basketball, volleyball, and soccer, at 6 months and full-contact sports participation at 8 months.
Clinical Evaluation

Before and 2 years after surgery, we measured the side-to-side difference (SSD) in anterior tibial translation on stress radiographs using a Telos Stress Device type SE 2000 (Telos, Hungen-Obbornhofen, Germany) at 20° knee flexion under an anterior drawer force of 150 N and evaluated anterior knee stability. Rotational stability was assessed by the manual pivot-shift 2 years after surgery. We evaluated pivot-shift test findings according to the method described by Yasuda et al., and categorized them as negative, +, and ++. Clinical results were determined by the Lysholm score 2 years after surgery.

All patients provided informed consent, and second-look arthroscopy at the time of staple removal was performed to assess ACL graft integrity independently of postoperative symptoms at a mean of 15.7 months (range, 12–23 months) after the initial operation. Synovial coverage and the presence of laceration of AMB graft were assessed during second-look arthroscopy because the AMB graft is more correlated to intercondylar roof impingement. A superficial graft laceration was defined as one with some superficial fiber and a substantial graft laceration as one with rupture of 1 or more strands.

At the same time, to detect subtle postoperative LOE quantitatively, we obtained a lateral radiograph, with the patient under general or lumbar anesthesia, of the reconstructed and contralateral uninjured knees in full extension while the patient’s heels were elevated above the table. For reproducibility, both posterior condyles of the femur were superimposed under fluoroscopy in every knee. We measured the extension angle, defined as the angle between the anterior cortex of the femur and the posterior cortex of the tibia (Fig. 2). LOE was defined as the difference in angles between the reconstructed and contralateral uninjured knees.

In addition, according to the Beighton and Honan criteria, patients with an extension angle of the uninjured knee of ≤10° comprised the group with 10° or less hyperextension (N group) and those with an extension angle of >10° comprised the group with more than 10° hyperextension (H group).
**Radiographic Measurement of Tibial Tunnel Position**

A true lateral radiograph was taken to evaluate the tibial tunnel position 1 year after surgery. We measured the anterior placement percentage (APP) of the tibial tunnel using the method reported by Amis and Jakob\(^\text{16}\) (Fig. 3). We measured both the length from the tibial anterior margin to the anterior edge of the tibial tunnel (A) and the anteroposterior length of the tibial plateau (TP) by measuring the line that runs parallel to the medial tibial plateau and passes through the anterior and posterior margins of the proximal end of the tibia. The sagittal percentage of the tibial tunnel was calculated as follows: APP of the tibial tunnel = A/TP × 100 (%).

Postoperative clinical outcomes were compared between the groups. All radiographic measurements were performed using an iRad-IA viewer (Infocom, Tokyo, Japan).

**Statistics**

All statistical analyses were performed using StatView software (SAS Institute, Cary, NC). Based on the previous literature\(^\text{3}\) that compared the clinical outcomes of ACL reconstruction with or without knee hyperextension, an a priori power analysis was conducted. It indicated that a sample size of at least 28 patients per group was necessary to detect the difference of SSD in anterior tibial translation between groups with \(\alpha = 0.05\), a power of 0.8.

Student’s \(t\)-test was used to compare the SSD in anterior tibial translation and the LOE between the groups. The Mann-Whitney \(U\) test was used to compare pivot-shift test results and Lysholm scores between the groups. The \(\chi^2\) test was used to compare second-look findings between the groups. The Pearson correlation coefficient was used to investigate the relationship between the LOE and extension angle of contralateral uninjured knee, SSD, and APP of the tibial tunnel. \(P\) values <0.05 were considered significant.

**RESULTS**
Of the 167 patients, 19 underwent single-bundle reconstruction. Fourteen patients had bilateral ACL injuries, 6 had multiple ligamentous injuries, 2 had proximal tibial fracture, and 8 had apparent radiographic osteoarthritic change. In addition, 9 were lost to follow-up monitoring: 4 moved to another location, while the reason for the loss of the other 5 was unknown. Nine declined to undergo second-look arthroscopy. The remaining 100 patients (45 males and 55 females), with a mean age of 26 ± 10 years (range, 13 to 49 years), were enrolled in this study. The mean duration of follow-up was 28 months (range, 24 to 48 months).

The mean extension angle of contralateral uninjured knees in all patients was 9.5 ± 5.3°. There were 58 patients in the N group and 42 patients in the H group. Mean extension angles in the N and H groups were 5.8 ± 2.9° and 14.7 ± 3.0°, respectively. The distributions of age and sex were not significantly different between the groups (Table 1). Accompanying medial meniscus tears were found in 25 knees in the N group and in 15 knees in the H group. In the N group, 16 menisci were partially resected and 9 were repaired during the ACL reconstruction. In the H group, 9 menisci were partially resected and 6 were repaired. Accompanying lateral meniscus tears were found in 11 knees in the N group and in 6 knees in the H group. In the N group, 7 menisci were partially resected and 4 were repaired during the ACL reconstruction. In the H group, 3 menisci were partially resected and 3 were repaired. APP of the tibial tunnel in the N and H groups were 25.5 ± 5.1% and 25.7 ± 3.4%, respectively, with no significant difference.

The postoperative mean SSD in anterior translation were 2.2 ± 2.9 for the N group and 2.8 ± 2.9 mm for the H group, with no significant difference (Table 1). In the N group, there was a significant positive correlation between the APP and the SSD ($r = 0.34; P = 0.01$) (Fig. 4A). However, in the H group, there was no significant correlation between these (Fig. 4B). On the pivot-shift test, 6 of 58 patients in the N group had a score of grade + and 1 patient had a
score of grade ++. In the H group, 5 of 42 patients had a score of grade + and 3 patients had a score of grade ++ (Table 1). The positive ratios on the pivot-shift test were not significantly different between the groups. Mean postoperative Lysholm scores in the N and H groups were 97.8 (85-100) and 98.4 (90-100), respectively, with no significant difference (Table 1).

The LOE in the N and H groups were \(-0.7 \pm 3.7^\circ\) and \(1.3 \pm 3.3^\circ\), respectively, with a significant difference \((P = 0.007)\) (Table 1). In the H group, there was a significant positive correlation between extension angle of the contralateral knee and LOE \((r = 0.33; P = 0.04)\) (Fig. 5). With respect to ACL graft integrity at second-look arthroscopy, 6 of 58 knees (10.3%) in the N group versus 13 of 42 knees (30.9%) in the H group had superficial graft laceration or partial synovial coverage of AMB graft, which were significantly different \((P = 0.01)\) (Table 1). We had no substantial laceration cases. Five patients (4 in the N group and 1 in the H group) had cyclops lesions that were resected. In the H group, postoperative clinical outcomes were not significantly different between knees with and without LOE (Table 2).

**DISCUSSION**

We found that anterior and rotational stability and Lysholm score after anatomic double-bundle ACL reconstruction for extreme knee hyperextension were not significantly different compared with those for normal to mild knee hyperextension. However, postoperative LOE in extreme knee hyperextension was significantly larger than that in normal to mild knee hyperextension, and ACL graft integrity of the former was inferior to that in the latter.

Traditionally, it has been advocated that the tibial tunnel in transtibial ACL reconstruction for knee hyperextension should be posteriorly placed to avoid roof impingement.\(^4\) However, there are no clinical reports proving whether posterior placement of the tibial tunnel is effective for knee hyperextension. Several authors have pointed out that it
results in vertical graft placement and inferior postoperative stability.\textsuperscript{17,18,19} On the other hand, recent anatomic and biomechanical studies led to increasing interest in anatomic ACL reconstruction in which the graft was placed in the native ACL footprint.\textsuperscript{6,7,8} Several studies on anatomic ACL reconstruction showed that anterior placement of the tibial tunnel results in greater sagittal graft obliquity and improved control of anterior tibial translation.\textsuperscript{9,20,21} Therefore, in this series, we created the tibial tunnel for the AMB at the anteromedial position of the ACL footprint without modification of the tunnel position according to the extension angle of each knee. As a result, APP of the tibial tunnel did not differ significantly between the groups, and it was equal to that in a cadaveric study that investigated the anterior edge of the ACL.\textsuperscript{22,23}

With regard to clinical results after ACL reconstruction for hyperextension, Kim et al. reported that patients with knee hyperextension had greater anterior translation after non-anatomic ACL reconstruction than those without knee hyperextension. In addition, they reported that a bone-patellar tendon-bone autograft (SSD, 3.4 mm) provided superior anterior stability compared with a hamstring tendon autograft (SSD, 4.4 mm).\textsuperscript{3} To our knowledge, the current work is the first reported clinical study to examine the postoperative outcome after anatomic double-bundle ACL reconstruction with semitendinosus tendon for extreme knee hyperextension, and shows that it can obtain the same postoperative knee stability as for normal to mild knee hyperextension. Furthermore, the postoperative SSD (2.8 mm) in anterior translation of our H group was smaller than that in the above-mentioned report. Our study suggests that anatomic double-bundle ACL reconstruction can obtain better anterior stability, even for extreme knee hyperextension, than non-anatomic ACL reconstruction.

We found that there was a significant positive correlation between the APP of the tibial tunnel and the SSD in anterior tibial translation in the N group (Fig. 4A). This means that increasingly anterior placement of the tibial tunnel improved anterior knee stability for the
knees with normal extension, as in a previous cadaveric study. However, in the H group, there was no significant correlation between these (Fig. 4B). In addition, postoperative LOE in the H group was significantly larger than that in the N group, and superficial laceration of AMB graft at second-look arthroscopy was significantly frequently seen in the H group compared with that in the N group. These findings suggest that anatomic double-bundle ACL reconstruction for extreme hyperextension results in an adverse effect caused by roof impingement. Iriuchishima et al. investigated roof impingement after anatomic double-bundle ACL reconstruction using magnetic resonance imaging with full knee extension, and reported that no graft deformation, except in 1 knee, was observed and no knees exhibiting extension loss were observed. However, the mean extension angle of the knees of their subjects was approximately 7°, and their study was not on extreme knee hyperextension. The mean extension angle of the knees in our H group was 14.7° and we quantitatively measured the LOE using radiographs, which may be why our results differ from those in the study by Iriuchishima et al.

Jagodzinski et al. reported that the average extension angle of the beginning of impingement in native ACL was 6.3 ± 3.8° from magnetic resonance cinematography. They also reported that there was a strong positive correlation between KT-1000 measurement of the anterior tibial displacement and the impingement laxity defined as the difference in extension between contact of the ACL with the intercondylar notch and maximum extension of the knee. This study means that the ACL stretched out in hyperextension after contacting the notch. Matsubara et al. also showed that the native ACL bows posteriorly, contacting the intercondylar notch in the knee when the knee is hyperextended more than 10°. These results indicate that congenital laxity of the knee is associated with impingement of the ACL and elasticity of the native ACL facilitates full hyperextension. Our study demonstrated that the patients with a contralateral knee with a larger extension angle retained larger LOE in the H
group (Fig. 5). Even if the anatomic ACL reconstruction restored the physiologic roof impingement, reconstructed ACL graft may not be able to exhibit the same viscoelastic properties as native ACL throughout the process of remodeling. To restore the physiologic laxity of the knee, further study is needed for extreme knee hyperextension with regard to the initial tension applied on the graft or the initial fixation angle of the knee.\textsuperscript{25} In this study, we tensioned each bundle at 30 N with the knee at 15° flexion for both normal to mild knee hyperextension and extreme knee hyperextension because biomechanical study\textsuperscript{13} has shown that average strains in the two bundles were equal at 15° knee flexion. For extreme knee hyperextension, it may be that the ACL graft should be fixed at a more extended angle of the knee to prevent LOE after ACL reconstruction because intra-articular graft length is greatest upon full hyperextension of the knee\textsuperscript{26,27}, or two bundle grafts should be separately fixed at different angles.

Shelbourne et al.\textsuperscript{28} reported that the prevalence of osteoarthritis on radiographs in the long term after ACL reconstruction showed a tendency to be statistically significantly higher in patients who had LOE of more than 2° at the time of initial return to full activity, at a mean of 6 months after surgery, and logistic regression showed that the odds of having osteoarthritis were 1.1. In our study, mean LOE in the H group was 1.3°, and clinical outcomes 2 years after surgery were not significantly different between knees with and without LOE. Long-term follow-up study is necessary to determine whether this slight LOE in the H group is associated with radiographic osteoarthritis or risk of re-rupture.

**LIMITATIONS**

Our study has some limitations. First, we had a relatively small sample size and short duration of follow-up. Second, the assessment of rotational stability was not quantitative. Third,
investigator blinding was not used. Fourth, we did not investigate whether the LOE on radiographic measurement was correlated with the LOE clinically measured using a goniometer. In addition, it is unknown whether this subtle LOE in the H group is clinically significant. Fifth, we did not evaluate roof impingement by imaging studies, such as MRI. However, even if roof impingement is evaluated using MRI with full knee extension, ACL-reconstructed knees were not necessarily restored to the same sagittal alignment in full extension or extension angle as contralateral uninjured knees. In particular, it will be difficult to evaluate roof impingement in knees for which reconstructed ACL is loose because tibial anterior translation in full knee extension may occur in such knees. Therefore, we assessed the impact of roof impingement from the ACL graft integrity at second-look arthroscopy.

CONCLUSION

Anatomic double-bundle ACL reconstruction for extreme knee hyperextension may obtain the same postoperative anterior and rotational stability as for normal to mild knee hyperextension. However, it increased superficial graft laceration.
REFERENCES


20. Bedi A, Maak T, Musahl V, et al. Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important?


**FIGURE LEGENDS**

**Fig. 1.** Arthroscopic view of (A) the femoral tunnels at 90° knee flexion, viewing from the anteromedial portal, and (B) the tibial tunnel positions, viewing from the anterolateral portal, in double-bundle reconstruction.

FAM, femoral tunnel for AMB; FPL, femoral tunnel for PLB; TAM, tibial tunnel for AMB; TPL, tibial tunnel for PLB.

**Fig. 2.** Lateral radiograph of contralateral uninjured knee in full extension. The (A) extension angle was measured as the angle between the (B) anterior cortex of the femur and the (C) posterior cortex of the tibia (D, line parallel to line C).

**Fig. 3.** The anterior placement percentage of the tibial tunnel was calculated from true lateral radiographs as the distance from the anterior margin of the tibia to the anterior edge of the tibial tunnel (A) divided by the anteroposterior length of the tibial plateau (TP) and multiplied by 100.

**Fig. 4.** (A) Correlation between the APP and the SSD in anterior translation in the N group. There was a significant positive correlation ($r = 0.34; P = 0.01$). (B) Correlation between the APP and the SSD in anterior translation in the H group. There was no significant correlation. APP, anterior placement percentage; SSD, side-to-side difference.

**Fig. 5.** Correlation between extension angle of the contralateral uninjured knee and the loss of extension in the H group. There was a significant positive correlation ($r = 0.33; P = 0.04$).
### TABLE 1
Demographic Data and Clinical Outcomes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>All knees (n = 100)</th>
<th>N group (n = 58)</th>
<th>H group (n = 42)</th>
<th>P value</th>
</tr>
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<tr>
<td>Age (range; y)</td>
<td>26.5 (13–49)</td>
<td>27.2 (13–48)</td>
<td>25.4 (13–48)</td>
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<td>Sex (male/female)</td>
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<td>28/30</td>
<td>17/25</td>
<td>0.44</td>
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<tr>
<td>SSD of anterior tibial translation (mm)</td>
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<td>2.2 ± 2.9</td>
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<td>0.21</td>
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<td>Pivot-shift test (no. of cases)</td>
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<tr>
<td>Negative</td>
<td>85</td>
<td>51</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>++</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td></td>
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<tr>
<td>Lysholm score</td>
<td>97.9 (85-100)</td>
<td>97.8 (85-100)</td>
<td>98.4 (90-100)</td>
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<td>LOE (°)</td>
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<td>-0.7 ± 3.7</td>
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<td></td>
<td></td>
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<tr>
<td>superficial laceration of AMB (no. of cases)</td>
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<td>6</td>
<td>13</td>
<td>0.01</td>
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SSD, side-to-side difference; LOE, loss of extension; AMB, anteromedial bundle.
<table>
<thead>
<tr>
<th>Parameter</th>
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<th>LOE-negative (n = 20)</th>
<th>P Value</th>
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<td>Age (range; y)</td>
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<td>23.6 ± 9.9</td>
<td>0.27</td>
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<td>Extension angle of the contralateral knee</td>
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<td>SSD of anterior tibial translation (mm)</td>
<td>2.7 ± 3.0</td>
<td>3.2 ± 2.8</td>
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<tr>
<td>Pivot-shift test (no. of cases)</td>
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<td>Lysholm score</td>
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<td>0.97</td>
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LOE, loss of extension; SSD, side-to-side difference; AMB, anteromedial bundle.
Fig 4A

SSD in anterior tibial translation (mm)

APP of the tibial tunnel (%)
Fig 5