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Augmentation of Anterolateral Structures of the Knee Causes Undesirable Tibiofemoral Cartilage Contact in Double-Bundle Anterior Cruciate Ligament Reconstruction—A Randomized In-Vivo Biomechanics Study

Jiayu Qiu, M.D., Cong Wang, Ph.D., Willem A. Kernkamp, Ph.D., Jiebo Chen, M.D., Caiqi Xu, M.D., Tsung-Yuan Tsai, Ph.D., and Jinzhong Zhao, M.D.

Purpose: To analyze the in vivo tibiofemoral cartilage contact patterns in knees undergoing double-bundle anterior cruciate ligament reconstruction (DB-ACLR) with or without anterolateral structure augmentation (ALSA).

Methods: Twenty patients with an ACL-ruptured knee and a healthy contralateral side were included. Nine patients received an isolated DB-ACLR (DB-ACLR group), and 11 patients had a DB-ACLR with ALSA (DB+ALSA group). At 1-year follow-up, a combined computed tomography, magnetic resonance imaging, and dual fluoroscopy imaging system analysis was used to capture a single-legged lunge of both the operated and healthy contralateral side. Tibiofemoral contact points (CPs) of the medial and lateral compartments were compared. CP locations were expressed as anteroposterior (AP, +/-) and medial–lateral (ML, +/-) values according to the tibia.

Results: In the DB-ACLR knees, no significant differences were found in CPs when compared with the healthy contralateral knees (P ≥ .31). However, in the DB+ALSA knees, the CPs in the lateral compartment had a significantly more anterior (mean AP: operative, -2.8 mm, 95% confidence interval [CI] -5.0 to -0.7 vs healthy, -5.0 mm, 95% CI -6.7 to -3.2; P = .006) and lateral (mean ML: operative, 23.2 mm, 95% CI 21.9-24.5 vs healthy, 21.8 mm, 95% CI 20.2-23.3; P = .013) location. The CPs in the medial compartment were located significantly more posterior (mean AP: operative, -3.4, 95% CI -5.0 to -1.9 vs healthy, -1.3, 95% CI -2.6 to -0.1; P = .006) and lateral (mean ML: operative, -21.3, 95% CI -22.6 to -20.0 vs healthy, -22.6, 95% CI -24.2 to -21.0; P = .021).

Conclusions: DB-ACLR restored the tibiofemoral cartilage contact mechanics to near-normal values at 1-year follow-up. Adding the ALSA to the DB-ACLR resulted in significantly altered tibiofemoral cartilage contact locations in both the medial and lateral compartments. Clinical Relevance: In DB-ACLR knees, the addition of an ALSA may be unfavorable as it caused significantly changed arthrokinematics.

See commentary on page 1237

Anterior cruciate ligament (ACL) deficiency results in increased anterior translation and internal rotatory laxity, causing anterolateral rotatory instability.1 Anterior cruciate ligament reconstruction (ACLR) aims to restore the excessive knee laxity to normal values. However, persistent postoperative anterolateral rotatory instability was found in approximately 25% of the patients who underwent ACLR.2

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Moreover, tibiofemoral cartilage contact patterns are not restored by single-bundle (SB) ACLR techniques.3 The increased residual laxity could result in poor functional outcomes and an increased prevalence of posttraumatic osteoarthritic changes.5 To improve the postoperative tibiofemoral knee kinematics (mainly, to improve rotatory laxity), double-bundle (DB) ACLR was proposed.5 However, conflicting clinical outcomes have been described.6

Alternatively, extra-articular procedures for anterolateral structure augmentation (ALSA), including anterolateral ligament reconstructions (ALLR) and lateral extra-articular tenodesis (LET) procedures, are performed in an effort to better control the increased rotatory laxity with favorable biomechanical effects.7 Some researchers reported promising clinical outcomes, as decreased ACL-graft ruptures8 and better survival of meniscal repair9 were observed in the combined ACLR with ALSA knees. However, others found no benefit on the rotatory control10 or even overconstrained knee motion11 after the procedure.

In addition to the conflicting time-zero biomechanical effect of an ACLR with an ALSA, the effects on the in vivo tibiofemoral cartilage of ALSAs remain unknown. Persistent minor changes in tibiofemoral contact kinematics are associated with increased cartilage deformation.12 Evaluation of joint kinematics and subsequent contact points (CPs) could help to determine whether an ACLR can restore joint contact mechanics effectively.13 Therefore, the purpose of this study was to analyze the in vivo tibiofemoral cartilage contact patterns in DB ACL-reconstructed knees with or without ALSA. The hypothesis was that the additional anterolateral traction given by ALSA graft would result in altered tibiofemoral cartilage contact mechanics compared with intact knees.

**Methods**

This study is an extended laboratory study of our previous randomized controlled trial (ChiCTR-IOR-16009982) that aimed to evaluate DB-ACLR’s clinical outcomes with or without ALSA for young active patients. Consecutive patients diagnosed with an ACL tear between February 2017 and June 2019 had been selected for ACLR.14 Those patients had been randomized to undergo an isolated DB-ACLR or a combined DB-ACLR with ALSA using a 1:1 ratio with randomized numbers processed via Excel (Office 2016; Microsoft Corp., Redmond, WA). The same surgical team performed all surgeries. Our institution’s ethics committee approved the amendment of this study protocol (2016-96-(1)).

As an extension of the background randomized controlled trial, the current study mainly focused on the effect of additional ALSA techniques on cartilage contact in vivo. Patients had DB-ACLR with or without ALSA were screened (Table 1), and written informed consent were obtained from patients before they participated this study. Cartilage contact patterns were derived from 6 degrees-of-freedom kinematics (6DOF) for both operated and healthy contralateral knees using the dual fluoroscopy imaging system (DFIS) and computed tomography (CT)/magnetic resonance imaging (MRI)-based 2-dimensional/3-dimensional matching technique. Patients were strictly selected to diminish the biomechanical effects of confounding factors like meniscal tears, chondral defects, and asymmetric knee alignments (Table 1, Fig 1).

The primary outcome measure of this study was the CP locations of operative knees. The secondary outcome measures consisted of contact variables derived from CP locations, physical examinations including Lachman, anterior drawer and pivot shift tests, and patient-reported outcome measures.

**Sample Size**

We justified the sample size according to previous studies using similar measurement techniques.13,15 After screening, group allocation was 9 patients in the DB-ACLR group and 11 in the DB-ACLR with ALSA group for surgery, respectively (Fig 1). The post-hoc power analysis suggested that by using 0.25 effect size and .05 significance level, 9 patients per group would be able to reach 80% power, which would be sufficient to determine abnormal cartilage contact locations.3,16

<table>
<thead>
<tr>
<th>Table 1. Inclusion and Exclusion Criteria</th>
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<tr>
<td><strong>Inclusion Criteria</strong></td>
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<tr>
<td>Age: 18-40 y</td>
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<tr>
<td>Grade 3 pivot shift sign before surgery</td>
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<tr>
<td>BMI between 20 and 30</td>
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<tr>
<td>Minimum 1-year postsurgery</td>
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<td>Returned to sports, including pivoting activities</td>
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<tr>
<td>Finished rehabilitation plan, no obvious symptoms and joint abnormality at previous follow-ups</td>
</tr>
<tr>
<td>Range of motion (ROM) &gt;120° for both knees</td>
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<tr>
<td>Signed informed consent for biplane fluoroscopy imaging tests</td>
</tr>
</tbody>
</table>

BMI, body mass index.
Surgical Procedures

Anatomic DB-ACLR

Anatomic DB-ACLR (Fig 2 A and B) was performed with 8-stranded hamstring tendons placed in the native ACL footprints. The anteromedial (AM) and posterolateral (PL) grafts were made from 4-strand semitendinosus tendon (ST) and 4-strand gracilis tendon, respectively (Fig 2A). On both the femoral and tibial sides, suspension fixation with cortical buttons (Arthrex, Naples, FL) over the outer orifices of the femoral tunnels was applied. Fixation of both AM and PL grafts were performed with full extension and neutral rotation of the knee under approximately 20 N traction force. One interference screw (Smith & Nephew, Andover, MA) was placed into the AM bundle tibial tunnel just behind the graft as reinforcement. A set of cortical buttons with an adjustable loop (Arthrex) was pulled through a transverse tibial tunnel from the medial to the lateral side and reduced to tension the grafts (Fig 2B).

Anterolateral Structure Augmentation

For anterolateral Structure Augmentation (Fig 2 C, D), the tunnel placement of ACL grafts also followed the native footprints. The graft placement of an additional ALSA (Fig 2D) is a response to the complex anterolateral concept. The designed femoral tunnel was located posterior to the apex of the lateral femoral epicondyle. The ALSA tibial tunnel’s proximal tunnel was located at the anterior edge of the tibial plateau, just medial to the Gerdy’s tubercle. In brief, a standard graft was used to reconstruct the ACL-PL bundle and the augmentation of ALS. The anterior half of the peroneus longus tendon was harvested, folded, and bundled together with the 2-strand gracilis tendon for the PL-ALS graft (Fig 2C). The graft passed superficial to the lateral collateral ligament and underneath the iliotibial band. After the placement of all grafts, sutures from each graft end were tied to their counterparts (Fig 2D) and fixed to the cortical button by an adjustable loop at full extension and neutral rotation of the knee.

The ALSA technique in the current study kept the iliotibial band’s integrity, which differs from published LET descriptions, and the graft orientation was different from ALLR. The intra-articular procedures (reconstructions of ACL-AM and PL bundles) consistently followed the native ACL footprints.

Postoperative Management

The patients were followed up at 1.5, 3, 6, and 12 months after surgery. Patients started full range of motion exercises and muscle strengthening immediately after surgery, running and jumping at 3 months, and noncontact sports at 6 months. Preoperative and 1-year postoperative knee functional scores (Lysholm and Marx rating scales) were evaluated. The Lysholm and Marx scales are valid as patient-administered scores and responsive after treatment of ACL tears to assess pain, swelling, limp, squatting, instability, stairs, support, and locking of the knee, as well as patients’ willingness to play sports. Knee stability was assessed by the anterior drawer, Lachman, and pivot shift tests by an experienced orthopaedic surgeon blinded to the type of surgery with tapes covering the surgical incisions. At 1-year follow-up, MRI scans were performed to evaluate the graft, meniscal, and chondral conditions. Also, tunnel positions of ACL-AM and PL bundles together with ALSA grafts were validated with postoperative CT scans of both.
sides of the knees using quadrant methods. All ACL grafts in the 2 groups were found within referenced anatomical insertions, and one femoral socket of ALSA was found deviated from the others, which has been excluded (Fig 1).

**Tibiofemoral Cartilage Contact Mechanics**

**Data Acquisition**

At 1-year follow-up, both operated and healthy contralateral knees were imaged using the DFIS (BV Pulsera, Philips, Amsterdam, the Netherlands) to determine 6DOF of the knee (Fig 3). CT scans (SOMATOM Definition AS+; Siemens, Munich, Germany) of both sides of the knee joints ranging from approximately 30 cm proximal and distal to the joint line (thickness, 0.6 mm; resolution, 512 × 512 pixels) were obtained to reconstruct 3-dimensional bone models (Fig 3) using Amira 6.7 (Thermo Fisher Scientific, Waltham, MA). MRI scans were also performed on 3.0-T superconducting MR scanners (Achieva, Philips Healthcare, Amsterdam, Netherlands) with 2-mm slice thickness and 0.5-mm gap spacing to generate cartilage models. A standard protocol was performed, including axial, coronal, or sagittal T1-weighted imaging, and axial, coronal, or sagittal T2-weighted imaging (with and without fat saturation). Three-dimensional bone and cartilage models were created using a combination of automated (thresholding) and manual segmenting techniques and were subsequently
co-registered to properly align MRI-derived cartilage models to CT-derived bone models as previously described.29

All participants were imaged using a custom dynamic biplane radiography system (30 images/s, 70 kV, 125 mA maximum, 10-millisecond pulse width) at 12 to 13 months after surgery during a standardized single quasistatic leg lunge motion. All patients were asked to practice the motion by keeping the foot of the tested limb still, upper trunk straight, lowering down the body, and pushing the foot of the contralateral limb through the toes backward to perform a lunge-down. After practice, the participants developed a well-established movement pattern by using either leg safe and secure. During the test, a handrail was placed at the front as external support, but patients were asked to keep the balance by themselves. Those who felt uncomfortable and failed to complete a smooth motion were excluded (Fig 1).

Fluoroscopy images were recorded and previewed to ensure the patients could keep the tested knees under DFIS surveillance. Three trials were collected each knee in each test session and one best was screened out for analysis.

Kinematic Variables
Tibial and femoral coordinate systems were defined according to previously published studies.28 Next, the fluoroscopic images, CT-, and MRI-based knee models of each subject were imported into MATLAB (R2018a; MathWorks, Natick, MA) to match the outlines of the fluoroscopic image.30 Dynamic 3D kinematics of the knee were interpreted by pairwise relative movements of local Cartesian systems of bone models as 6DOF data, which included anteroposterior translation, proximal–distal translation, medial–lateral translation, flexion–extension movement, varus–valgus movement, and internal–external rotation.31

Contact Variables
Tibiofemoral CPs were determined as the center of cartilage contact by identifying the distance-weighted centroid of the overlapping cartilage areas as described previously.29 Tibial joint CPs were described with 5° flexion interval using a Cartesian coordinate system aligned with the tibial plateau (Fig 4A). On the axial view, tibial CPs were expressed as AP and ML values for comparisons. The local femoral Cartesian system was converted to cylindrical coordinate system (Fig 4B).32 All contact locations were normalized using the average size of all tested individuals.33

The magnitude of tibial anteroposterior and medial–lateral CP translation (range minimum to maximum AP and ML values for 0-90° of flexion) were calculated for comparisons of general contact patterns (Fig 5). For CPs on the sagittal plane, anteroposterior translation...
excursions (APEs) also were calculated. The differences between femoral APEs and tibial APEs calculated as the sliding length. The sliding lengths of both medial and lateral compartments were analyzed to determine the grand total of interface movements and rolling-sliding interactions during 0–90° flexion (Fig 4C). The smaller sliding lengths suggests less gliding and more pure rolling of the articular surface throughout the motion, indicating less shearing. The medial–lateral difference of sliding lengths between compartments was also calculated (Fig 4C) as an indicator of total knee axial rotation.

**Statistical Analysis**

A 2-way repeated measures analysis of variance was performed with surgical and contralateral knees as one factor and flexion degrees as repeated measures (side * flexion degree) for tibial contact locations (AP and ML values) in both groups. Separate 2-way mixed-model analyses of variance (surgery * type) were performed to evaluate differences in AP contact range, ML contact range, medial and lateral compartmental sliding length, and inter-compartmental sliding difference (ΔSliding). Main effects were evaluated for surgery (reconstructed vs contralateral knee) for the 2 groups combined.
Bonferroni $P$ value adjustment was adopted for multiple comparisons. An independent $t$ test was used to compare normally distributed variables, whereas the Mann–Whitney $U$ test was performed for non-normally distributed data. Side-to-side (reconstructed vs contralateral) differences of mentioned variables were also compared between groups when significant differences were detected between limbs. Analyses were completed using SPSS (version 24.0; IBM Corp., New York, NY). Significance was defined as $P < .05$ for all analyses.

**Results**

During the DFIS test, 1 of the patients in DB-ACLR group failed to keep the knee motion within the fluoroscopic surveillance, and 2 patients in each group failed to finish a smooth continuous lunge. The final sample size for analysis was 9 for DB-ACLR group and 11 for DB+ALSA group (Fig 1). There were no significant differences in basic patient demographics between the 2 groups (Table 2). For the 2 groups combined, the average time period of performing one 0-90° lunge-down was $2.1 \pm 0.6$ seconds for the intact knees and $2.3 \pm 0.7$ seconds for the operated knees, with no significant difference detected ($P = .325$).

**Primary Outcomes**

**Contact Locations in DB-ACLR Knees**

The CP locations were not significantly different for both the medial and lateral compartments when compared with the healthy contralateral knees (Fig 6). At the lateral tibial plateau, the AP value of operated knee was on average $-4.5$ mm (95% confidence interval $-6.7$ to $-2.3$), compared with $-5.5$ mm ($-6.6$ to $-4.4$) in healthy contralateral side ($P = .31$); for the ML value, this was $23.0$ mm (95% confidence interval $20.9$-$25.1$) for the operated side and $21.9$ mm ($20.0$-$23.9$) for the healthy contralateral side ($P = .37$).

At the medial tibial plateau, the AP value was on average $-2.2$ mm (95% confidence interval $-4.0$ to $-0.3$) for the operated knee compared with $-1.9$ mm ($-4.3$ to $-0.5$) in healthy contralateral side ($P = .712$);

**Table 2. Subject Demographics**

<table>
<thead>
<tr>
<th></th>
<th>DB-ACLR (n = 9)</th>
<th>DB+ALSA (n = 11)</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, male/female, n</td>
<td>5/4</td>
<td>7/4</td>
<td>$-$</td>
</tr>
<tr>
<td>Side of operation, left/right, n</td>
<td>2/7</td>
<td>6/5</td>
<td>$-$</td>
</tr>
<tr>
<td>Injury to operation time, mo</td>
<td>$6.1 \pm 2.9$</td>
<td>$6.6 \pm 2.3$</td>
<td>.769</td>
</tr>
<tr>
<td>Body mass index</td>
<td>$24.4 \pm 2.6$</td>
<td>$23.3 \pm 2.1$</td>
<td>.662</td>
</tr>
<tr>
<td>Size of AM bundle, mm</td>
<td>$8.0 \pm 0.5$</td>
<td>$7.9 \pm 0.5$</td>
<td>.651</td>
</tr>
<tr>
<td>Size of PL bundle, mm</td>
<td>$6.6 \pm 0.4$</td>
<td>$6.5 \pm 0.4$</td>
<td>.616</td>
</tr>
<tr>
<td>Size of ALS, mm</td>
<td>$-$</td>
<td>$4.6 \pm 0.9$</td>
<td>$-$</td>
</tr>
<tr>
<td>Age at DFI testing, y</td>
<td>$28.0 \pm 4.2$</td>
<td>$31.2 \pm 4.4$</td>
<td>.117</td>
</tr>
</tbody>
</table>

NOTE. Numeric data are presented as mean ± standard deviation unless otherwise indicated.

ACLR, anterior cruciate ligament reconstruction; ALS, anterolateral structure; ALSA, anterolateral structure augmentation; AM, anteromedial; DB, double bundle; DFI, dual-fluoroscopic imaging; PL, posterolateral.
for the ML value, this was \(-22.7\) mm (95\% confidence interval \(-25.3\) to \(-20.1\)) for the operated knee compared with \(-22.4\) mm (\(-24.9\) to \(-19.9\)) in healthy side \(P = .71\). However, significantly smaller \((P < .02)\) ML values of medial tibial CPs were found in lower flexion angles (at every 5° between 10°–30° of flexion).

**Contact Locations in DB-ACLR with ALSA Knees**

The CP locations were significantly different for both the medial and lateral tibia plateaus in the DB-ACLR with ALSA knees compared with the healthy contralateral knees (Fig 7). At the lateral tibial plateau, the AP value of the operated knee was on average \(-2.8\) mm (95\% confidence interval \(-5.0\) to \(-0.7\)), which was significantly larger \((P = .006)\) than \(-5.0\) mm (\(-6.7\) to \(-3.2\)) in the healthy contralateral side, and, to be specific, the CPs were positioned significantly anteriorly \((P < .037)\) in every 5° between 30°–90° of knee flexion in DB+ALSA operated knees. The ML value of the operated knee was on average 23.2 mm (95\% confidence

<table>
<thead>
<tr>
<th>Contact Variables, mm</th>
<th>DB-ACLR Reconstructed</th>
<th>DB-ACLR Contralateral</th>
<th>DB+ALSA Reconstructed</th>
<th>DB+ALSA Contralateral</th>
<th>(P) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral AP range</td>
<td>9.91 ± 3.44</td>
<td>10.56 ± 3.12</td>
<td>8.49 ± 3.48</td>
<td>10.77 ± 2.87</td>
<td>.212</td>
</tr>
<tr>
<td>Medial AP range</td>
<td>9.55 ± 3.16</td>
<td>9.58 ± 2.59</td>
<td>8.85 ± 2.02</td>
<td>9.90 ± 1.77</td>
<td>.535</td>
</tr>
<tr>
<td>Lateral ML range</td>
<td>5.60 ± 2.25</td>
<td>6.07 ± 2.24</td>
<td>5.94 ± 1.79</td>
<td>4.50 ± 2.07</td>
<td>.518</td>
</tr>
<tr>
<td>Medial ML range</td>
<td>3.76 ± 1.20</td>
<td>3.50 ± 1.68</td>
<td>4.39 ± 1.72</td>
<td>3.60 ± 1.13</td>
<td>.322</td>
</tr>
<tr>
<td>Lateral sliding</td>
<td>22.52 ± 3.15</td>
<td>22.79 ± 4.03</td>
<td>23.71 ± 1.65</td>
<td>22.77 ± 3.46</td>
<td>.768</td>
</tr>
<tr>
<td>Medial sliding</td>
<td>26.76 ± 2.22</td>
<td>28.38 ± 3.27</td>
<td>29.01 ± 3.10</td>
<td>29.08 ± 2.73</td>
<td>.414</td>
</tr>
<tr>
<td>(\Delta) Sliding</td>
<td>4.24 ± 3.29</td>
<td>5.59 ± 3.19</td>
<td>5.30 ± 4.24</td>
<td>6.31 ± 5.09</td>
<td>.388</td>
</tr>
</tbody>
</table>

**Table 3. Contact Variables Derived From CP Locations for Two Groups**

NOTE. Numeric data are presented as mean ± standard deviation unless otherwise indicated. For the 2 groups combined, no significant difference was found for all contact variables between operative and contralateral knees.

ACLR, anterior cruciate ligament reconstruction; ALSA, anterolateral structure augmentation; AP, anteroposterior; CP, contact point; DB, double bundle; ML, medial–lateral; \(\Delta\) Sliding, medial–lateral sliding difference.

Fig 6. Anteroposterior values and ML values of lateral (A, C) and medial (B, D) contact points at every 5° of flexion from 0 to 90° in the DB-ACLR group. Values were expressed by mean values (lines) and 95\% confidence intervals (bands). \(\dagger\)Significant differences in certain flexion angles of the operated and healthy contralateral knees. (ACLR, anterior cruciate ligament reconstruction; DB, double bundle; ML, medial–lateral.)
interval 21.9-24.5), which was significantly larger ($P = .013$) than 21.8 mm (20.2-23.3) in the healthy contralateral side, and to be specific, the CPs were positioned significantly laterally ($P < .028$) in every 5° between 25° and 75° of knee flexion in DB+ALSA-operated knees.

At the medial tibial plateau, the AP value of the operated knee was on average $-3.4$ mm (95% confidence interval $-5.0$ to $-1.9$), which was significantly smaller ($P = .006$) than $-1.3$ mm ($-2.6$ to $-0.1$) in the healthy contralateral side, and to be specific, the CPs were positioned significantly posteriorly ($P < .045$) in every 5° between 0° and 50° of knee flexion in DB+ALSA-operated knees. The ML value of the operated knee was on average $-21.3$ mm (95% confidence interval $-22.6$ to $-20.0$), which was significantly larger ($P = .021$) than $-22.6$ mm ($-24.2$ to $-21.0$) in the healthy contralateral side, and to be specific, the CPs were positioned significantly laterally ($P < .039$) in every 5° between 35° and 70° of knee flexion in DB+ALSA-operated knees.

**Secondary Outcomes**

**Contact Variables**

No significant difference (Fig 5, Table 3) was found between the reconstructed (both DB-ACLR with and without ALSA) and contralateral knees in lateral ($P = .212$) and medial ($P = .535$) AP ranges, lateral ($P = .518$) and medial ($P = .322$) ML ranges, lateral ($P = .768$) and medial ($P = .414$) sliding lengths, and inter-compartmental sliding differences ($P = .388$).

**Physical Examinations and Patient-Related Outcome Measures**

No positive anterior drawer and Lachman tests were found in check-ups in either group. No patients had a residual positive pivot shift test in the operated knees. Statistically significant functional improvements of Lysholm and Marx scores were found in both groups before and 1-year after operation (Table 4). The differences in Lysholm scores were also defined as clinically significant, which exceeded the minimal detectable change (MDC) threshold. No significant
Table 4. Functional Rating Scores (Lysholm and Marx Scales) of 2 Groups

<table>
<thead>
<tr>
<th></th>
<th>Lysholm</th>
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<tr>
<td></td>
<td>Preop</td>
<td>Postop</td>
<td><em>P Value</em></td>
<td>Preop</td>
<td>Postop</td>
<td><em>P Value</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Within-Group</em></td>
<td></td>
<td></td>
<td><em>Within-Group</em></td>
</tr>
<tr>
<td>DB-ACLR</td>
<td>70.3 ± 14.2</td>
<td>90.1 ± 5.5</td>
<td>.007*</td>
<td>24.6 ± 20.1</td>
<td>53.3 ± 20.9</td>
<td>.032*</td>
</tr>
<tr>
<td>DB+ALSA</td>
<td>75.4 ± 13.7</td>
<td>91.7 ± 4.9</td>
<td>.006*</td>
<td>21.7 ± 17.4</td>
<td>54.2 ± 19.4</td>
<td>.004*</td>
</tr>
<tr>
<td>P value (between-group)</td>
<td>.517</td>
<td>.882</td>
<td></td>
<td>.782</td>
<td>.919</td>
<td></td>
</tr>
</tbody>
</table>

*NOTE. Numeric data are presented as mean ± standard deviation unless otherwise indicated. Preoperative scores were evaluated before surgery, and postoperative scores were rated 12 months after surgery. ACLR, anterior cruciate ligament reconstruction; ALSA, anterolateral structure augmentation; DB, double bundle.*

*Significant difference for functional scores before and 12 months after surgery.

Differences regarding preoperative and postoperative functional scores were found between the 2 groups (Table 4).

**Discussion**

The most important finding of the study was that the combined DB-ACLR with ALSA significantly affected the CPs compared with the healthy contralateral knee at 1-year follow-up. In contrast, the isolated DB-ACLR resulted in near-normal CPs. Therefore, the addition of the ALSA in patients with high-grade pivot shifts undergoing DB-ACLR may not be beneficial and might result in detrimental effects.

According to studies by Hosseini et al.3 and Van de Velde et al.,12 we already know that ACL deficiency would cause abnormal postero-lateral contact locations in both medial and lateral compartments referring to healthy contralateral knees. Hosseini et al.3 and Hosshino et al.13 also reported persisting abnormal cartilage contact locations in ACLR operated knees, whereas in current study, contact locations were normal in the DB-ACLR-reconstructed knees (Fig 6), indicating that the abnormal knee kinematics had been restored. This may be explained in part by the anatomical DB-ACLR technique,17 which was different from the aforementioned SB-ACLR studies. Another reason may be that the tested lunge motion in this study is less strenuous than downhill running, which was performed by others.13,35

Very few studies had focused on the in vivo kinematics or cartilage contact involving the additional ALSA techniques during daily activity. In the DB-ACLR with ALSA knees in the current study, the CPs were positioned anteriorly in the lateral tibia but posterior in the medial compartment compared to the healthy contralateral side, indicating tibial lateral rotation after ALSA (Fig 7). A recent study15 also detected anterior shift of CPs in the lateral tibia 6 months after a combined SB-ACLR and modified Lemaire LET surgery. However, the CPs in the medial compartment was reported not changed. Such findings corresponded to our study in part of laterally-rotated tibias after lateral side augmentation. In contrast, the CPs in the current study were found lateral in both medial and lateral tibial plateaus of ALSA knees, suggesting medially shifted tibias with respect to the femurs (Fig 7) in part contradicts the aforementioned study by Nishida et al.15 This could be explained by different surgical techniques involving SB- or DB-ACLR with different types of lateral procedures and different tested motions (lunge vs downhill running). However, a previous study36 employing both time-zero in vitro and DFIS in vivo tests also reported increased medial translations concomitant with increased anterior translations of the tibia in ACL-deficient knees. Previous in vivo analysis on cartilage contact mechanics found that even minor shifts in cartilage contact result in significantly increased deformation of tibiofemoral cartilage.12 Relevantly, previous clinical trials or meta-analyses showed an increased risk of lateral37 or medial2 compartment osteoarthritis (OA) in combined ACLR and LET knees at long-term follow-up. However, others involving similar surgical procedures have not found an increased rate of OA development.38,39 Hence, for the DB-ACLR with ALSA knees in the current study, whether altered CPs in specific movements would potentially cause long-term OA changes requires further investigation with longitudinal follow-up. The ALSA technique may cause the adverse effects observed in the current study; therefore, future studies should analyze the optimal tunnel locations for an ALSA. The effects of other surgical procedures on the knees also require further investigation.

Different outcomes of in vivo rotatory stability also have been described for ACLR knees. Compared with intact knees, studies indicated an increase13 or decrease40 in tibial axial rotations or compartmental sliding differences in isolated ACLR operative knees. LET and ALLR techniques have been described and are used in clinics to address ALRI.7 Recent systematic reviews and meta-analyses have shown that anterolateral surgical interventions are generally effective in rotatory constraint and reduce graft failure.2,23 For the current study, after ACLR, all grade 3 positive pivot shift signs detected before surgery had turned negative at the 1-year follow-up with or without ALSA,
agreeing with the study of Sheean et al.\textsuperscript{10} Similarly, no significant difference in medial–lateral compartmental sliding distances were found (Table 3). Therefore, these data demonstrated that the isolated DB-ACLR can be a good solution for those patients with a high-grade pivot-shift. Considering that the DB-ACLR with ALSA is a demanding surgical procedure, the ALSA might be easier to practice in conjunction with a SB-ACLR.\textsuperscript{41} The in vivo biomechanics of SB-ACLR with ALSA requires further investigation. The anterolateral surgical procedure itself might also be more applicable among those with greater risks of graft failure.\textsuperscript{19,42} Besides, graft healing and neuromuscular adaptations may reduce the effect of ALSA on cartilage biomechanics over time.\textsuperscript{15} Hence, longitudinal analysis involving multiple time points is desirable.

Restoration of the knee sliding-rolling patterns is another important postoperative measurement to indicate long-term joint health.\textsuperscript{43} Contact variables such as the magnitude of contact ranges have been generally evaluated in AP ranges and interchanged to sagittal rolling-gliding interactions.\textsuperscript{42} The compartmental sliding lengths (Slidings) were calculated for quantification of the shearing between cartilage surfaces.\textsuperscript{44} Hoshino et al.\textsuperscript{13} observed increased tibiofemoral sliding distance in both SB- and DB-ACLR knees during downhill running. In the current study, such measurements in reconstructed knees showed no significant difference with the measurements in the contralateral, healthy knees, independent of whether an ALSA was performed (Table 3). Hence, we postulate that during noncompetitive weight-bearing flexions, compartmental rolling-gliding patterns could generally be restored by the DB-ACLR using 8-strand hamstring autograft, with or without ALSA. Whether DB-ACLR or the additional ALSA changes cartilage shearing in higher-level motions requires further study, which shall include greater demand activities such as running and hopping.

Limitations

This study has several limitations. First, there is a limited number of patients in this study, and factors as activity level and anatomic specificity (such as tibial slope) were not included. Second, we conducted in vivo tests with only lunge motion at only one time point (1-year after surgery). Preoperative data were not collected considering fear, pain, and limited knee flexion of those recruited patients. Third, the current data only presented the biomechanical effect of an additional ALSA.

Conclusions

DB-ACLR restored the tibiofemoral cartilage contact mechanics to near-normal values at 1-year follow-up. Adding the ALSA to the DB-ACLR resulted in significantly altered tibiofemoral cartilage contact locations in both the medial and lateral compartments.

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References


