Repair of Focal Cartilage Defects With Scaffold-Assisted Autologous Chondrocyte Grafts

Clinical and Biomechanical Results 48 Months After Transplantation

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Background: Scaffold-assisted autologous chondrocyte implantation is a clinically effective procedure for cartilage repair, but biomechanical evaluations are still missing.

Purpose: This study was conducted to assess the clinical efficacy, including biomechanical analyses, of BioSeed-C treatment for traumatic and degenerative cartilage defects of the knee.

Study Design: Case series; Level of evidence, 4.

Methods: The authors evaluated the midterm clinical and biomechanical outcome of BioSeed-C, a cell-based fibrin-polymer graft for the treatment of cartilage defects. Clinical outcome at 4-year follow-up was assessed in 52 patients with full-thickness cartilage defects, International Cartilage Repair Society (ICRS) stage III and IV. Clinical scoring was performed preoperatively and 48 months after Implantation using the Lysholm score, the International Knee Documentation Committee (IKDC) score, the ICRS score, the Knee Injury and Osteoarthritis Outcome Score (KOOS), and the Noyes score. Cartilage regeneration was assessed by magnetic resonance imaging (MRI) using the Henderson-Kreuz score. Biomechanical evaluation was performed by isokinetic strength measurements, comparing healthy and operated knee of each patient.

Results: Clinical evaluation showed significant improvement in the Lysholm (from 51.8 preoperatively to 80.7 at 48 months postoperatively), IKDC (from 47.5 to 71.5), ICRS (from 3.8 to 2.0), KOOS (subcategory pain from 62 to 78, symptoms from 68 to 76, activities of daily living from 68 to 85, sports from 19 to 55, and quality of life from 30 to 55), and Noyes score. Cartilage regeneration was assessed by magnetic resonance imaging (MRI) using the Henderson-Kreuz score. Biomechanical evaluation was performed by isokinetic strength measurements, comparing healthy and operated knee of each patient.

Conclusion: The clinical outcomes 4 years after graft implantation are good despite a persisting strength deficit. Implanting BioSeed-C is a promising treatment option for cartilage defects of the knee. More emphasis should be put on the rehabilitation of muscular strength.

Keywords: scaffold-assisted autologous chondrocyte implantation; BioSeed-C; clinical efficacy; focal cartilage defects; midterm results; isokinetic strength measurement

Cartilage has a low self-healing capacity. In clinical routine, a variety of surgical techniques for articular cartilage repair have been established, including bone-marrow-stimulating techniques, osteochondral autograft transfer, and common autologous chondrocyte implantation (ACI).

Treatment options have to be chosen individually, depending on the defect size, depth, and location. Especially for large cartilage defects, cell-based cartilage repair approaches based on matrices support the formation of hyaline-like repair tissue and provide long-term clinical effects and patient improvement. As reported by Minas in 2003, more than 15 000 patients worldwide have been treated with ACI since Britberg et al. introduced this technique in 1987. Since the establishment of the procedure, a variety of clinical studies...
have confirmed the clinical efficacy of implanting autologous in vitro-expanded chondrocytes for the regeneration of cartilage defects. In the first-generation and second-generation ACI, the prepared defect is covered with a periosteal flap or a collagen sheet that is fixed to the intact cartilage rim before the autologous chondrocyte cell suspension is injected. The use of ACI may therefore be difficult in some regions of the knee, especially in defect locations lacking a stable cartilage shoulder. Disadvantages of this first-generation treatment option were periosteal hypertrophy, ablation, and loss of cells into the joint cavity leading to a revision surgery rate of up to 25% to 40%.

Therefore, in scaffold-assisted ACI, cartilage-engineering grafts combining ACI with stable 3-dimensional matrices were developed to overcome these disadvantages. These grafts ensure the 3-dimensional distribution of the in vitro-cultured chondrocytes, provide an initial mechanical stability for an easy handling by the surgeon, and promote chondrocyte differentiation and subsequent formation of hyaline-like cartilage repair tissue. Based on this concept, scaffold-assisted chondrocyte implantation with scaffolds of hyaluronic acid, collagen, and resorbable polymers were shown to be clinically efficient for the repair of cartilage defects.

In BioSeed-C (BioTissue Technologies GmbH, Freiburg, Germany), the chondrocytes are embedded in a stable fibrin-polymer matrix, which allows an arthroscopic implantation and ensures a secure fixation of the graft. In a horse model, formation of a hyaline-like cartilage matrix as well as firm bonding of the graft to the adjacent healthy cartilage and subchondral bone could be shown. Recently, midterm clinical results with 2-year follow-up and clinical outcome after 4 years in an osteoarthritis subgroup confirmed the clinical efficacy of this scaffold-assisted ACI. Until now biomechanical studies with muscle strength measurement are missing for all ACI techniques.

The aim of this prospective study was to evaluate the midterm clinical outcome of BioSeed-C for the treatment of focal cartilage defects of the knee including clinical, functional, and biomechanical analyses.

MATERIALS AND METHODS

Patients

In this prospective study, the effectiveness of scaffold-assisted ACI (BioSeed-C) for the treatment of chondral defects of the knee 4 years after transplantation was investigated.

Implantation of BioSeed-C

From December 2001 to October 2002, 79 patients suffering from shouldered, focal posttraumatic or degenerative symptomatic cartilage defects of the knees with Outerbridge classification IV were treated with BioSeed-C. Two-year follow-up data of this particular patient population (n = 40 patients) as well as analysis of the osteoarthritis subgroup at 4 years (n = 19 patients) were published previously. In this study, 52 patients gave consent to a clinical follow-up of 4 years. For 19 of 52 patients, radiographs were available showing a Kellgren-Lawrence score of 2 or 3. These defects were classified as focal degenerative, osteoarthritic defects. Clinical and functional evaluations were performed comparing the patients' situations preoperatively and at 48 months after transplantation by clinical and functional scores, Mri score, and comparative isokinetic examinations of the knees. The patient characteristics are presented in Table 1.

The average age of the patients (25 females and 27 males; mean body mass index [in kg/m²] of 24.56, ranging from 19-34) was 35.59 years (range, 17-51 years). The mean defect size of the first lesion was 4.76 cm² (range, 2-15 cm²) with Outerbridge classification IV. Chondral defects were located on the femoral condyles, and resorbable polymers were shown to be clinically efficient for the repair of cartilage defects.

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isolated. For autologous chondrocyte cultivation, 100 mL of whole blood was collected with a conventional blood sampling system (Sarstedt AG, Numbrecht, Germany). After in vitro expansion, approximately 20 million chondrocytes were rearranged in a 3-dimensional polymer-based scaffold, made of polyglycolic/polyactic acid (polyglactin, Vicryl [Ethicon GmbH, Norderstedt, Germany]) and polydioxanone by fibrin gluing. After debridement of the cartilage defect zone down to the subchondral bone, the in vitro cultured graft (2 cm × 3 cm × 0.2 cm thick) was cut to the size of the defect and implanted through arthroscopy or arthroscopy into the defect area. The use of the arthroscopic approach or mini-open arthroscopy depended on the location and size of the defects. In total, 72 of 79 patients received BioSeed-C by arthroscopy, while arthroscopy was used in 7 patients. Arthroscopic implantation was performed when defects were located on the medial/lateral condyle and when only 1 graft was sufficient to cover the defect. For stable fixation, the graft was fixed with resorbable suture material by a previously described anchor-knot technique.15,22,26

Follow-up Treatment After Transplantation of BioSeed-C

The day after surgery, rehabilitation started, including mobilization on crutches with a maximal loading 15% body weight, continuous passive motion, and range of motion (ROM) exercises. The ROM was limited to 30° after retropatellar transplantation. Passive ROM exercises were gradually increased to self-assisted exercises. Continuous passive motion for 6 hours per day and partial loading with 15% body weight was maintained for 6 weeks.24,46 After this period, patients gradually increased the loading and performed increased strength training as well as active physiotherapy and gentle ergonomic training at an appropriate level for the next 6 weeks. Starting as week 13, patients increased weightbearing and performed strength training and coordination exercises up to full weightbearing. After 6 months, cycling or jogging was allowed, followed by more strenuous activities and contact sports after the first rehabilitation year. Patient compliance for rehabilitation was not monitored.

Evaluation of Clinical, Functional, and Biomechanical Results

Clinical outcome could be evaluated in only 50 of 52 patients, because in 2 patients total knee replacement was necessary during the follow-up period. Clinical results were evaluated by the International Knee Documentation Committee (IKDC) score,21 the International Cartilage Repair Society (ICRS) Knee Examination Form,1 the Lysholm score,27 the Noyes activity rating score,2 and the Knee injury and Osteoarthritis Outcome Score (KOOS).42 For each score, the data were documented preoperatively and at 48 months after surgery.

After 4 years of follow-up, 43 patients gave consent to participate in isokinetic testing and 44 patients allowed secondary MRI. At 4 years after transplantation, MRI of the knee was accomplished with a 1.5-T scanner (Siemens AG, München, Germany) and the data were evaluated using the modified Henderson and Kreuz scoring system.19,24 For biomechanical evaluation, maximum strength was measured in 2 different concentric and 1 eccentric test modes at 60 and 180 deg/s using an isokinetic dynamometer (CON-TREX MJ Multi-joint Module, CMV AG, Dübendorf, Switzerland). Five reciprocal flexion and extension movements were performed with the healthy and the operated knee in the different test modes (concentric 60 deg/s, concentric 180 deg/s, and eccentric 60 deg/s). Thereby, reciprocal knee flexion and extension movements were performed to measure quadriceps and hamstring strength capacities in Newton-meters.
RESULTS

Clinical Evaluation

4 Years After Implantation of BioSeed-C

The clinical outcome 4 years after implantation of BioSeed-C in focal cartilage defects was evaluated using the IKDC knee evaluation score and the ICRS score (Figure 1). The IKDC score (Figure 1A) showed significant improvement at 4 years ($P \leq .001$) postoperatively compared with preoperative findings in 50 patients, showing an increased mean score from 47.5 to 71.5. The IKDC scores were rated abnormal in 98% of the patients at baseline and improved to a normal or nearly normal rating in over 80% of the patients at follow-up. In addition, the
ICRS score improved significantly ($P \leq .001$) over the observational period from 3.8 preoperatively to 2.0 at 4-year follow-up (Figure 1B).

Four years after graft transplantation, clinical evaluation as assessed by the Lysholm score showed statistically significant improvement ($P < .001$). Compared with the patients' preoperative situation, the median Lysholm score improved significantly ($P < .001$) from 51.8 to 80.7 in the study population (Figure 2).

Further clinical and functional evaluation was assessed by the KOOS and the Noyes score. After 48 months, the patients' status improved significantly ($P < .001$) compared with preoperative findings in the subcategories pain, activities of daily life (ADL), sports and recreation (Sports/rec), and quality of life (QoL) (Figure 3). The mean scores increased in the subcategories pain from 62 to 78; ADL, from 68 to 85; Sports/rec, from 19 to 55; and knee-related QoL, from 30 to 55 at 4 years after implantation of the graft. Patients also showed a significant improvement in the subcategory symptoms (from 68 to 76) as analyzed by paired $t$ test ($P < .05$) at 4-year follow-up. Individual preoperative and 4-year follow-up scores (ICRS, IKDC, KOOS, and Lysholm) are given in the supplementary material (see Appendix 1, available in the online version of this article at http://ajs.sagepub.com/supplemental).

For further functional analysis, the Noyes activity rating score was used (Figure 4). At 48 months after implantation, the Noyes score improved significantly ($P \leq .001$) with increased median scores going from 31 preoperatively to 69 after the observational period of 4 years.

Magnetic Resonance Imaging and Evaluation 4 Years After Graft Transplantation

A detailed MRI analysis according to Henderson and Kreuz is given in Table 2. Therein, 44 of 52 patients were analyzed by MRI 4 years after implantation of BioSeed-C. Two patients had to undergo revision surgery and received a total knee endoprosthesis and a further 6 patients without pain or clinical problems refused to provide radiologic data for our 4-year follow-up. These patients are not included in the table data. Patients with focal cartilage defects treated with BioSeed-C showed moderate to complete filling of the defects. Thirty-two of 44 patients showed a complete filling of the defect with cartilage repair tissue. In 11 patients, the defects were filled incompletely but more than 50% and 1 patient showed a defect filling of less than 50%. The cartilage signal in 26 defects was normal or showed slight alterations in the intensity in 15 patients. In 3 defects, the signal was hyperintense in larger areas of the repair tissue. Strong to moderate subchondral edema was evident in 8 patients and 36 of 44 patients showed no or mild edema. Seven patients showed moderate to strong signs of knee joint effusion. No or mild knee joint effusion was evident in 37 of 44 patients treated with BioSeed-C at 4-year follow-up. Both patients who received a total knee replacement after 4 years had the last MRI control 12 months postoperatively. In these 2 patients, the defects were partially filled (<50%).
biomaterials such as collagen, polymers with fibrin glue, used in the mentioned studies are composed of different
5 years after matrix-associated ACI. The scaffolds or hyaluronic acid. Nevertheless, all techniques belong to
These findings support the good results of Behrens et al, Kon et al, and Ossendorf et al, who reported a mean Lysholm score of 78 points at 2-year follow-up and improvement of KOOS values for pain from 64.3 preoperatively to 78.2 postoperatively; for symptoms, from 68.2 to 78.9; ADL, from 67.6 to 80.6; Sports/recreational, 25.3 to 45.7; and QoL, from 29.9 to 52.9. This shows that the patients' improvement remained stable and that the good results found in the short-term follow-up at 2 years could be confirmed in the midterm at 4-year follow-up.

Previously, we reported the 4-year clinical outcome of a subgroup of the study population with focal degenerative and/or osteoarthritic cartilage defects. Interestingly, when comparing the traumatic and the osteoarthritic subgroups, we found no significant differences in the values for ICRS, IKDC, Lysholm score, and KOOS. This may indicate that the treatment with BioSeed-C leads to good clinical results in traumatic defects as well as in shouldered, focal degenerative defects.

The mean Lysholm score in our study was higher than the value of 63 reported by Pascual-Garrido et al, 31 also 4 years after ACI. The mean age of their patients was even lower in their collective but they included only patients treated for patellofemoral defects. This confirms the results of previous studies reporting worse results after ACI in patellofemoral compared with femoral condyle defects. Furthermore, the Lysholm score in our study was better compared with the average Lysholm score of 69.5 reported by Peterson et al, 41 in their long-term follow-up of first-generation ACI. An explanation for these different results might be the use of another ACI technique or differences in the make-up of the patient cohort. The problems of first-generation ACI using a periosteal flap with hypertrophic changes, delamination, and osseous overgrowth are not described with the scaffold-assisted ACI technique.

The KOOS results 4 years after using BioSeed-C showed that not only the knee function improved, but also subjective pain was reduced. The presented results for the

### DISCUSSION

In the present study, we showed the benefit and reliability of the use of the autologous gel polymer–based tissue-engineering graft BioSeed-C for the treatment of full-thickness posttraumatic or degenerative cartilage defects in the knee. All of the 4 validated scores used in this study showed a statistically significant improvement (P < .05) 4 years after scaffold-assisted ACI. The mean IKDC score increased from 47.5 preoperatively to 71.5 at 48 months. The IKDC scores were rated abnormal in 98% of the patients at baseline and improved to a normal or nearly normal rating in over 80% of the patients at follow-up. These findings support the good results of Behrens et al, Kon et al, and Gobbi et al, who found normal or nearly normal values in 70% of the patients at 36 months, 81% at 60 months, or 91% at 60 months and mean IKDC values of 69 points, 77 points, and 80 points 5 years after matrix-associated ACI. The scaffolds used in the mentioned studies are composed of different biomaterials such as collagen, polymers with fibrin glue, or hyaluronic acid. Nevertheless, all techniques belong to scaffold-assisted ACI and have been shown to be effective in the treatment of isolated cartilage defects in the knee.

Lysholm score values were 80.7 points at follow-up compared with preoperative values of 51.8 points. This shows that the loading capacity of the treated knee joint is well maintained at midterm. At 4-year follow-up, the KOOS improved in the subcategories pain, from 62 preoperatively to 78 postoperatively; symptoms, from 68 to 76; ADL, from 68 to 85; Sports/recreational, to 19 to 55; and QoL, to 30 to 55. In the same study group at a 2-year follow-up, Ossendorf et al reported a mean Lysholm score of 78 points at 2-year follow-up and improvement of KOOS values for pain from 64.3 preoperatively to 78.2 postoperatively; for symptoms, from 68.2 to 78.9; ADL, 67.6 to 80.6; Sports/recreational, 25.3 to 45.7; and QoL, from 29.9 to 52.9. This shows that the patients' improvement remained stable and that the good results found in the short-term follow-up at 2 years could be confirmed in the midterm at 4-year follow-up.

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The mean Lysholm score in our study was higher than the value of 63 reported by Pascual-Garrido et al, also 4 years after ACI. The mean age of their patients was even lower in their collective but they included only patients treated for patellofemoral defects. This confirms the results of previous studies reporting worse results after ACI in patellofemoral compared with femoral condyle defects. Furthermore, the Lysholm score in our study was better compared with the average Lysholm score of 69.5 reported by Peterson et al in their long-term follow-up of first-generation ACI. An explanation for these different results might be the use of another ACI technique or differences in the make-up of the patient cohort. The problems of first-generation ACI using a periosteal flap with hypertrophic changes, delamination, and osseous overgrowth are not described with the scaffold-assisted ACI technique.

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### TABLE 2

<table>
<thead>
<tr>
<th>Rating</th>
<th>Defect Filling</th>
<th>Signal Intensity</th>
<th>Subchondral Edema</th>
<th>Effusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Normal</td>
<td>32 (complete filling), including 4 with minimal hypertrophy and 2 with subchondral cysts</td>
<td>26 (normal)</td>
<td>14 (no edema)</td>
<td>10 (no effusion)</td>
</tr>
<tr>
<td>2 Mild</td>
<td>11 (&gt;50%), including 3 with minimal hypertrophy and 2 with subchondral cysts</td>
<td>16 (small hyperintense areas)</td>
<td>22 (mild edema)</td>
<td>27 (mild effusion)</td>
</tr>
<tr>
<td>3 Moderate</td>
<td>1 (&lt;50%)</td>
<td>3 (hyperintense areas)</td>
<td>7 (moderate edema)</td>
<td>6 (moderate effusion)</td>
</tr>
<tr>
<td>4 Abnormal</td>
<td>0 (no filling)</td>
<td>0 (no signal)</td>
<td>1 (distinct edema)</td>
<td>6 (moderate effusion)</td>
</tr>
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</table>

with a hyperintensive repair tissue and showed a concomitant moderate subchondral edema.

### Biomechanical Evaluation

4 Years After Implantation of BioSeed-C

In 43 of 62 patients, maximum strength of the knee flexors and extensors at 4-year follow-up was assessed isokinetically (3 different test modes: concentric 60 deg/s, concentric 120 deg/s, and eccentric 60 deg/s) using the CON-TREX multijoint dynamometer (Figure 5). Two patients had to undergo revision surgery and received a total knee endoprosthesis, and in a further 7 patients no biomechanical data could be assessed because of limited patient compliance with participation. Data evaluation by Wilcoxon test comparing healthy and treated knees of each patient revealed significantly (P < .05) higher peak torques in the healthy knee in all test modes. The differences in maximum strength were not as high in knee flexion as in knee extension (Figure 5B), indicating an imbalance of the quadriceps and hamstring on the operated side (Figure 5A).
transplantation of BioSeed-C leads to good clinical results in the short term and in the midterm.

The MRI evaluation revealed 52 patients with complete filling of the cartilage lesion. Patients with incomplete filling tended to have a persistent subchondral edema. Although speculative, incomplete filling may be associated with small gaps in the repair tissue or in the bonding area down to the subchondral bone plate and could result in a direct connection to the joint fluid and may provide a persistent stimulus for the subchondral bone.

In our study population, some concomitant surgical procedures such as high tibial osteotomy or patella balancing were performed. We are aware that these procedures may influence the final result, but these interventions were necessary to provide all patients with the same biomechanical requirements and comparable loading of the treated cartilage lesion in the postoperative follow-up. We believe that these interventions—even though resulting in additional scars—lead to a more homogeneous study group compared with a study population in which axial and patella malalignment are not addressed in the treatment. Furthermore, some patients underwent additional microfracture in the secondary lesions. However, the treated lesions were small defects less than 1 cm² and concerned only 5 patients. In addition, only a few cases received BioSeed-C by an arthroscopic approach. Therefore, we cannot conclude whether the mode of implantation may have an effect on morbidity or clinical results. Further studies have to elucidate whether arthroscopic or arthrotomic implantation of scaffold-assisted ACI leads to better strength, optimal fixation, and superior clinical outcome.

To get further objective information about the function of the treated knees, we performed biomechanical testing showing statistically significant reduction of maximum strength of the injured leg of the ACI patients. It has previously been shown in various knee disorders that lower muscular strength is associated with a poorer outcome. In particular the fact that quadriceps muscle weakness is considered a primary risk factor of knee joint osteoarthritis leads to the conclusion that strength training and a consequent rehabilitation process are crucially important in patients with cartilage damage of the knee. One of the aims of this study therefore was to objectively assess muscular strength capacities in our patients after standardized cartilage repair of the knee. To our knowledge, this is the first study showing remarkable strength deficits at midterm follow-up after scaffold-assisted ACI. The only other available study including isokinetic measurements of ACI patients is the recently published study by Loken et al, where 21 patients were evaluated isokinetically 1, 2, and 7.4 years after first-generation ACI. They also found highly significant side-to-side differences for knee flexion and extension strength. Strength deficits of the operated knee decreased from year 1 to year 2 and then remained constant at 7.4 years. Obviously, all tests were performed in their investigation in a concentric mode. In our study, we mainly confirmed the results of Loken et al and additionally assessed strength in eccentric contraction, bearing in mind that this is the mode that requires more coordination in more demanding situations so that strength deficits...
might be more pronounced. The strength deficit was greater in knee extension than in knee flexion, but also the healthy leg was affected by the muscular weakness. Müller et al.\textsuperscript{28} reported mean peak torque values of about 160 N-m for concentric and 200 N-m for eccentric knee extension using the same dynamometer and the same setting. For knee flexion, the average peak torque in healthy knees in their study was 115 N-m for concentric and 150 N-m for eccentric contraction. These values are far higher than the values measured in our study and suggest that patients 4 years after ACI suffer from quadriceps and hamstring weakness that is more obvious on the operated side and for knee extensors but also present in the nonoperated knee and in knee flexors.

Because our study lacks preoperative isokinetic data, it cannot be concluded from the results of this study whether the measured deficits are due to muscular atrophy, functional/neuromuscular impairments, or an underlying preoperative weakness. A preexisting deficit, though, is highly supposable considering the low values of the KOOS Sports/rec and Noyes score preoperatively, indicating that obviously pain prevented the patients from participating in sports activities. Additionally, various studies showed that proprioception is altered in injured knees and after knee joint surgery,\textsuperscript{2,5,7,11} suggesting that also neuromuscular coordination (eg, coordinated muscle fiber innervation and recruitment) is disturbed in ACI patients. This problem of soft tissue damage and invasive surgery could be resolved with improved mini-open and arthroscopic techniques for cell implantation. Finally, it can be assumed that the measured deficits are due to muscular atrophy, functional/neuromuscular impairments, or an underlying preoperative weakness. These hypotheses should be addressed in further studies including preoperative strength measurements as well as objective assessment of proprioception.

Another reason for the persistent quadriceps weakness could be the short period of postoperative treatment under the guidance of a physical therapist, which was limited to a maximum of 6 months. After this period, the patients trained on their own and the training as well as its intensity were no longer controlled by a specialist. However, tissue remodeling and cartilage regeneration takes years after implantation.\textsuperscript{25} Therefore, for future treatment, we suggest a more detailed rehabilitation program over 2 years with continuous monitoring and repetitive patient checks with special emphasis on the quadriceps force and specified patient instructions. In summary, the present results underline the importance of a postoperative rehabilitation plan with restoration of muscular strength and proprioception after ACI. Strength training should begin preoperatively and should be performed as far as pain can be tolerated and healing of the transplant is not jeopardized.

REFERENCES


Cartilage Pressure Distributions Provide a Footprint to Define Female Anterior Cruciate Ligament Injury Mechanisms

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Background: Bone bruises located on the lateral femoral condyle and posterolateral tibia are commonly associated with anterior cruciate ligament (ACL) injuries and may contribute to the high risk for knee osteoarthritis after ACL injury. The resultant footprint (location) of a bone bruise after ACL injury provides evidence of the inciting injury mechanism.

Purpose/Hypothesis: (1) To analyze tibial and femoral articular cartilage pressure distributions during normal landing and injury simulations, and (2) to evaluate ACL strains for conditions that lead to articular cartilage pressure distributions similar to bone bruise patterns associated with ACL injury. The hypothesis was that combined knee abduction and anterior tibial translation injury simulations would demonstrate peak articular cartilage pressure distributions in the lateral femoral condyle and posterolateral tibia. The corollary hypothesis was that combined knee abduction and anterior tibial translation injury conditions would result in the highest ACL strains.

Study Design: Descriptive laboratory study.

Methods: Prospective biomechanical data from athletes who subsequently suffered ACL injuries after testing (n = 9) and uninjured teammates (n = 390) were used as baseline input data for finite element model comparisons.

Results: Peak articular pressures that occurred on the posterolateral tibia and lateral femoral condyle were demonstrated for injury conditions that had a baseline knee abduction angle of 5°. Combined planar injury conditions of abduction/anterior tibial translation, anterior tibial translation/internal tibial rotation, or anterior tibial translation/external tibial rotation or isolated anterior tibial translation, external tibial rotation, or internal tibial rotation resulted in peak pressures in the posterolateral tibia and lateral femur. The highest ACL strains occurred during the combined abduction/anterior tibial translation condition in the group that had a baseline knee abduction angle of 5°.

Conclusion: The results of this study support a valgus collapse as the major ACL injury mechanism that results from tibial abduction rotations combined with anterior tibial translation or external or internal tibial rotations.

Clinical Relevance: Reduction of large multiplanar knee motions that include abduction, anterior translation, and internal/external tibial motions may reduce the risk for ACL injuries and associated bone bruises. In particular, prevention of an abduction knee posture during initial contact of the foot with the ground may help prevent ACL injury.

Keywords: bone bruise; ACL; articular cartilage; knee injury

Anterior cruciate ligament (ACL) injury is a common, often devastating, injury. It is well documented that women demonstrate a 4- to 6-fold higher injury rate compared with men participating in similar sports.12,18,26 During the ACL injury event, the large external forces that incite ligament disruption likely also lead to violent impact of the tibial and femoral articular cartilage, which transfers into the subchondral bone and often causes a bone bruise “footprint” that is a result of the mechanism of injury (Figure 1).43 Clinical imaging studies of acute ACL injury demonstrate that hyperintense signals in the subchondral tibia and femur (bone bruises) occur in more than 50% of patients who sustain complete ACL disruption.49 Bone bruises are commonly found on the posterolateral tibia and lateral femoral condyle on imaging studies after acute ACL injury (Figure 1) and likely reflect the tibial and femoral cartilage impact that occurs at the time of injury.20,33,49 The locations of bone bruises may provide insight into the directions (anatomic planes) that lead to ACL injury.

The objectives of this study were (1) to analyze tibial and femoral articular cartilage pressure distributions during normal landing and injury simulations and (2) to