

Arthroscopic Fixation of Matrix-Associated Autologous Chondrocyte Implantation: Importance of Fixation Pin Angle on Joint Compression Forces

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Purpose: The aim of the study was to investigate the effect of pin fixation perpendicular and 30° tilted to the matrix surface on the joint compression forces. **Methods:** In a porcine knee model, joint compression forces were recorded with a digital pressure sensor above the medial meniscus and with axial compression of 100 N by use of a material testing machine. The forces were recorded for an intact femoral condyle, as well as a standardized cartilage defect of 25 × 20 mm, after matrix-associated autologous chondrocyte implantation (m-ACI) (BioSeed C; Biotissue Technologies, Freiburg, Germany), fixed by use of a conventional suture technique and pin fixation with a biodegradable pin perpendicular and 30° tilted to the matrix surface. **Results:** In knees with cartilage defects, the peak compression forces (mean, 824 kPa) were significantly increased compared with the intact knee joint (564 kPa). After m-ACI implantation with a chondral suture (581.3 kPa) and perpendicular pin fixation, the joint compression forces of the cartilage defect were significantly decreased (630.7 kPa). There were no significant differences compared with the intact knee. After 30° tilted pin insertion, mean joint compression forces were significantly increased (1,740 kPa). **Conclusions:** This study shows that after chondral suture and perpendicular pin fixation, there are no increased compression forces in the knee joint in comparison to an intact knee. Thirty degree tilted pin insertion contributes to increased joint compression forces. **Clinical Relevance:** A tilted insertion during pin fixation in m-ACI should be avoided because it may lead to increased joint compression forces, especially after cartilage defect lesions on the tibial side.

The autologous chondrocyte implantation (ACI) introduced by Brittberg et al.¹ in 1994 is a well-established method for treatment of large chondral defects. During the last few years, several different

techniques have been developed.²⁻⁸ Whereas, in the initial described technique, a flap of periosteum is sutured over the defect and, finally, cartilage cells are implanted into the defect area²; in the recently developed techniques, periosteum is replaced with a collagen membrane such collagen I/III membrane.^{4,9} In the third generation, ACI chondrocytes are cultured in vitro in 3-dimensional matrices.^{10,11}

Several studies evaluate the clinical outcomes of ACI and compare them with microfracture of the chondral defect and with mosaicplasty.¹²⁻¹⁸ Whereas a prospective, randomized clinical trial comparing ACI and mosaicplasty has shown significant superiority of an ACI approach, studies comparing ACI against microfracture fail to find significant differences between both groups. Knutsen et al.¹⁸ even found significantly better improvement of Short Form 36 physical components in the microfracture group in comparison to

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the ACI group in their 2-year follow-up. However, there may be interference of the results because of the increased morbidity of open matrix-associated autologous chondrocyte implantation (m-ACI) fixation techniques compared with arthroscopic microfracture. Recently, arthroscopic techniques for m-ACI fixation have been developed.^{6,19} Besides a transosseous-suturing technique,¹⁹ a fixation technique using biodegradable pins can be used.⁶ A recent biomechanical study has shown significantly increased structural properties of pin fixation when compared with conventional suturing of the matrix.⁸ However, arthroscopic pin insertion is technically demanding, and concerns exist regarding cartilage damage on the tibial plateau after pin fixation.

Therefore, scientifically evaluating the potential pitfalls of a surgical technique is important. A pin misinsertion may occur if the surgeon does not control the knee flexion angle while inserting the pin; the pin will be fixed in a wrong insertion angle less than 90° to the surface. These projecting pins appear on arthroscopic viewing as a risk for corresponding cartilage damage. As result of scientific meeting discussions, some surgeons even see a risk for the corresponding cartilage from the perpendicularly inserted pin heads.

The purpose of this study was to evaluate joint compression forces after perpendicular biodegradable pin fixation and after fixation with a pin 30° tilted to the matrix surface. We hypothesize that perpendicular insertion of a biodegradable pin for the fixation of m-ACI will not significantly increase joint compression forces compared with the intact knee. Furthermore, we hypothesized that an insertion 30° tilted to the matrix surface will significantly increase joint compression forces.

METHODS

Testing Protocol

In this study 15 fresh porcine knees were used for testing joint compression forces after different fixation techniques of m-ACI. The mean age of the animals was 25 ± 2 weeks. The material was obtained from a local butcher, fresh frozen at -20°C , and thawed for 12 hours at room temperature before testing.

Before removal of muscles and soft tissues of the knee, it was mounted at 30° of knee flexion in a material testing machine (Z005; Zwick/Roell, Ulm, Germany) using a custom-made device and a 2-component polyurethane rapid structure foam (H400-AT; VOSS Chemie, Uetersen, Germany) for distal embed-

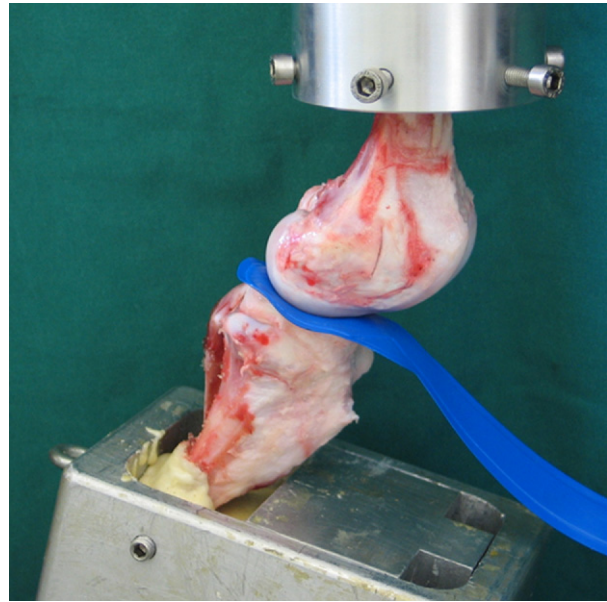


FIGURE 1. Test setup with specimen fixed in custom-made device in 30° of knee flexion and pressure sensor between condyle and tibia plateau.

ding. The defined angle was standardized because of the extension deficit of the porcine knee (Fig 1).

For single condylar testing, parts of the lateral femoral condyle in the knee joint were resected, leaving the medial meniscus attachment and the cruciate ligaments intact. Joint compression forces were recorded with a capacitive digital pressure sensor (AJP sensor; Novel, Munich, Germany) above the medial meniscus (Fig 1). The pliance ankle joint sensor (sensor size, $2.8 \times 4.3 \times 1 \text{ cm}^3$) model of sensor with 178 individual capacitive sensors and a saturation pressure of 2,500 kPa is established for measuring the intra-articular pressure distribution as published previously.²⁰ During dynamic simulations of joint movements in vitro, the active pressure sensor allows continuous data collection. With its great flexibility, it is possible to bend and conform it to the joint surface.²¹ The sensor was calibrated and tested for sensitivity in the Department of Experimental Musculoskeletal Medicine, Westfaelische Wilhelms-University Muenster, Muenster, Germany. Martinelli et al.²¹ used this setup in an ankle model that is comparable concerning size and surface to our model. Upon the recommendation of Novel, we used a 20-N/s loading rate because of the accuracy of the sensor and, furthermore, to control the loading mechanism, not to exceed the maximum applied load limit of the sensor.

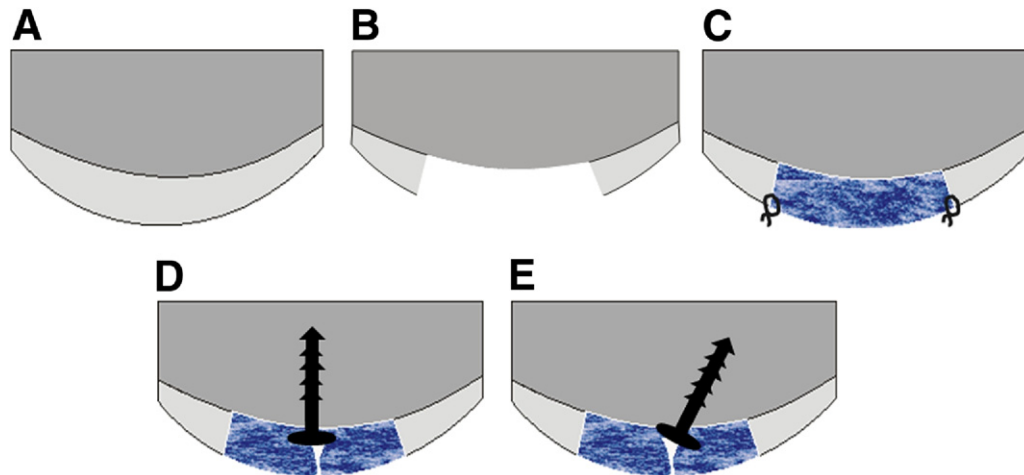


FIGURE 2. Tested groups: (A) intact cartilage, (B) cartilage defect, (C) matrix fixed by sutures, (D) matrix fixed with perpendicular pin, and (E) matrix fixed with 30° tilted pin.

The material testing machine (Zwick/Roell Z005) applied a maximum axial load of 100 N to the sensor. This compression force correlates to the physiologic unicondylar load during postoperative treatment after m-ACI (20-kg partial load, bicondylar, for 6 weeks). Initially, a preload of 1 N was applied to the specimens. In the following testing protocol, the specimens have been loaded up to 100 N with 20 N/s. All tests were based on the same loading protocol. Peak contact pressure, mean pressure in the area of interest, and area of measurement were documented. Furthermore, the difference in pressure between peak contact pressure and mean pressure were calculated. The area of interest was defined as the 1.0×1.0 -cm² area around the peak contact pressure. This area corresponds to 9 pressure-measuring squares.

The forces were recorded for the intact medial femoral condyle (Fig 2A), after creation of a standardized full-thickness cartilage defect of 2.5×2.0 cm² (Fig 2B), and after m-ACI (BioSeed C; BioTissue Technologies, Freiburg, Germany) (Figs 2C-2E). For matrix fixation, a chondral suture technique and a pin fixation technique by use of a biodegradable pin (16-mm SmartNail; ConMed Linvatec, Largo, FL) perpendicular and 30° tilted to the matrix surface were performed (Fig 2).

Testing Groups

During our study, the resulting intra-articular pressure has been tested in 15 porcine knees. In every specimen 5 different modifications have been investigated consecutively (groups A through E) (Fig 2).

After testing the intact femoral condyle as a control group (group A), a defined rectangular cartilage defect was created in the weight-bearing cartilage zone of the medial femoral condyle up to the subchondral bone (group B), by use of a custom-made device (Fig 2). The $2.5 \times 2.0 \times 0.2$ -cm biodegradable polyglycolic acid scaffold was reconstituted for 5 to 10 minutes with 0.9% sodium chloride to obtain its elastic and malleable properties. All tests were performed with unseeded scaffolds because of the missing effect by the cells on initial biomechanical properties of the scaffold material.¹⁷ A conventional chondral suture technique as described by Brittberg et al.¹ was performed for the fixation of the scaffold (group C). For this study, 4 edges of the scaffold were sutured with polydioxanone (Monofil, Ethicon, Norderstedt, Germany) (No. 6-0 USP) to the uninjured cartilage. This fixation technique was chosen to test possible positive changes of compression forces in the knee joint by matrix implantation.

Subsequently, a fixation technique using biodegradable poly-lactide pins (SmartNail; Linvatec ConMed) as described by Petersen et al.⁶ was performed (group D).

For fixation of the matrix to the porcine medial femoral condyle, a specific drill guide (Linvatec ConMed) was placed on the scaffold at a perpendicular angle. After 1.2-mm K-wire drilling, the biodegradable pin (16 mm in length) was carefully tapped into the subchondral bone. In 1 group the pin fixation was perpendicular to the matrix surface. In the other group the pin fixation was performed at a 30° tilted

angle corresponding to a 60° angle to the matrix surface (Fig 2). The insertion angle was controlled by use of a position device with a 60° and 90° angle to the condyle ground. The pins were completely inserted until the head had been in full contact with the cortical bone. We could not detect any damage to the implanted matrix in any tested construct. To exclude any interference of the results, the order of perpendicular and tilted pin fixation was alternated.

Statistics

Statistical analysis was performed at the Department of Medical Informatics and Biomathematics (Westfaelische Wilhelms-University Muenster) by use of SPSS Software for Windows, release 15.0.1 (SPSS, Chicago, IL). Before statistical testing, each continuous variable was analyzed in an explorative manner for its normal distribution (Kolmogorov-Smirnov test). Categorical variables were expressed as frequency and percentage, whereas continuous variables were presented as mean \pm SD. The Mann-Whitney *U* test was used for comparison of nonparametric variables (peak contact pressure, difference in pressure) between each study group. The significance level was $P < .05$.

RESULTS

Peak Contact Pressure

After creation of the standardized cartilage defect, mean peak contact pressure in the knee joint (824 ± 162.0 kPa) was significantly increased compared with the intact knee (564 ± 152.0 kPa) ($P < .05$) (Fig 3). After m-ACI with conventional suture and perpendicular pin fixation, the joint compression forces of the cartilage defect were significantly decreased. Mean peak contact pressures after suturing and perpendicular pin fixation were 581.3 ± 79.6 kPa and 630.7 ± 94.5 kPa, respectively. The relative mean peak contact pressure was 3% increased after suturing compared with the intact knee and 11% increased after perpendicular pin fixation. No significant differences could be detected compared with the intact knee ($P > .05$). After suture fixation, the relative mean peak contact difference was decreased by 29.5% when compared with the cartilage defect state. After perpendicular pin fixation, it was decreased by 25.6%. For both types of fixation, this difference was statistically significant ($P < .05$).

The mean peak contact pressure after matrix fixation with a 30° tilted pin to the matrix surface was $1,740 \pm 542.4$ kPa. The relative mean peak contact forces after 30° tilted pin fixation were increased by

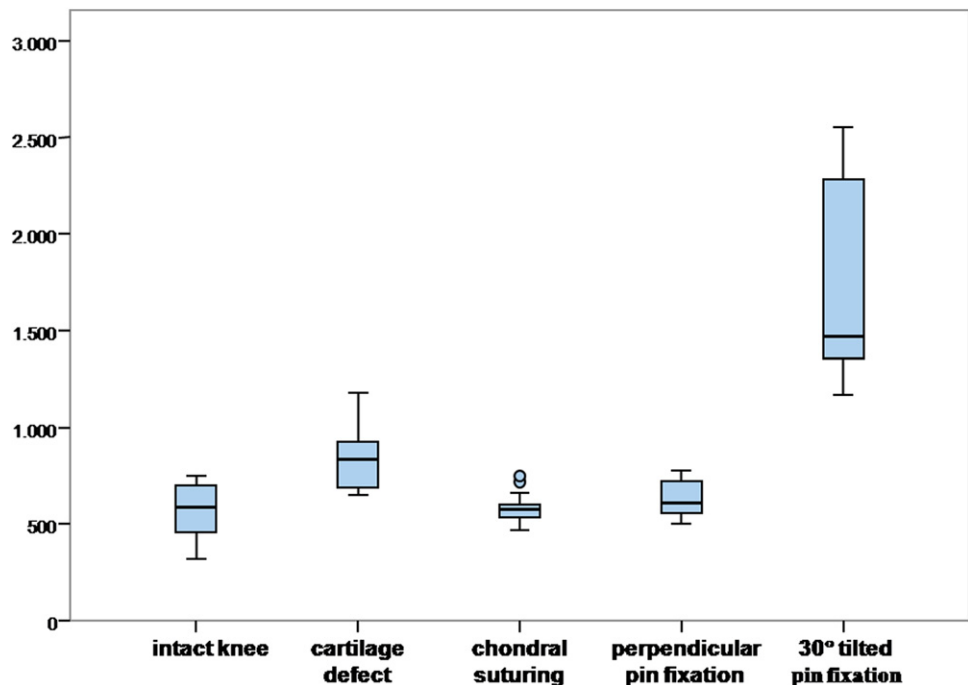


FIGURE 3. Box-plot diagram of results of peak contact pressure in all tested groups. There is no significant difference in groups A (intact knee), C (chondral suturing), and D (matrix fixed with perpendicular pin). They showed significantly decreased peak contact pressure in comparison to group B (cartilage defect). In group E (matrix fixed with 30° tilted pin) a significantly higher peak contact pressure has been determined in comparison to all other groups ($P < .05$).

208.5%, 199.3%, and 175.8% compared with the intact knees, those with suture matrix fixation, and those with perpendicular pin matrix fixation. These differences were highly significant compared with the other 3 groups ($P < .05$) (Fig 3).

Differences in Pressure Between Peak Contact Pressure and Mean Pressure in Area of Interest

The difference in pressure between peak contact pressure and mean pressure in the area of interest was 157.6 ± 90.7 kPa for the intact knee. This value was significantly lower than the values calculated in all other groups ($P < .05$). After cartilage defect, the difference in pressure was significantly higher (422.6 ± 144.8 kPa) ($P < .05$). In the conventional suture group (225.3 ± 64.6 kPa) and the perpendicular pin fixation group (254.1 ± 68.2 kPa), the difference in pressure was significantly lower than that in the cartilage defect group. No significant difference could be found between the suture and perpendicular pin fixation groups ($P > .05$). The difference for 30° tilted pin fixation of the matrices was $1,425.9 \pm 535.0$ kPa. The difference in pressure for 30° tilted pin fixation was highly significant in comparison to all other groups ($P < .05$) (Fig 4).

DISCUSSION

The aim of this study was to evaluate joint compression forces in the knee joint after m-ACI with biodegradable pin fixation perpendicular and 30° tilted to the matrix surface. The results support our initial hypothesis that perpendicular pin fixation does not lead to significantly increased joint compression forces.

Furthermore, the study could show that 30° angled pin fixation to the surface of the matrix resulted in significantly increased joint compression forces compared with the intact and conventional suturing technique or a perpendicular pin-fixed m-ACI (Fig 5).

These results are of high clinical interest. Pin fixation of m-ACI seems to be a safe surgical technique; however, a tilted insertion of the pin needs to be avoided.

To our knowledge, these are the first investigations of peak pressure problems after tilted insertion of pin fixation in the case of m-ACI or other indications. The clinical correlation of the increased joint compression forces as reported in this in vitro study could represent potential damage to the corresponding cartilage or meniscal tissue. A previous study in cadaveric bones has shown an apparently smooth surface of the matrix-pin construct.¹ However, when the pin is not properly

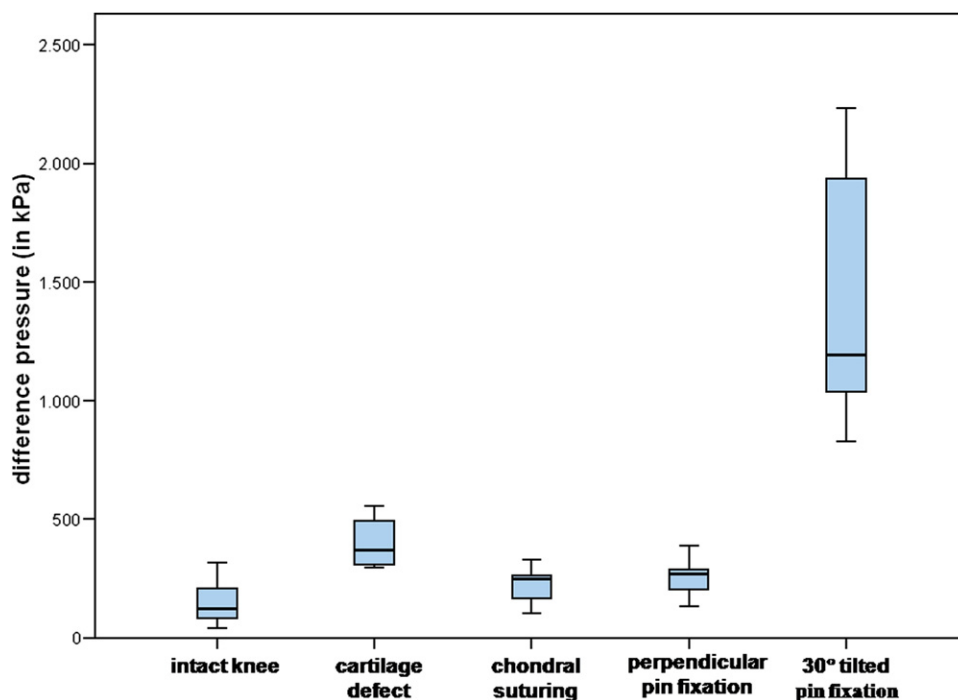


FIGURE 4. Box-plot diagram of results of differences in pressure between peak contact pressure and mean pressure in area of interest. There is no significant difference in groups A (intact knee), C (chondral suturing), and D (matrix fixed with perpendicular pin). They showed significantly decreased peak contact pressure in comparison to group B (cartilage defect). In group E (matrix fixed with 30° tilted pin) a significantly higher peak contact pressure has been determined in comparison to all other groups ($P < .05$).

FIGURE 5. Three-dimensional illustration of contact forces after (A) perpendicular pin fixation (group D) and (B) 30° tilted pin fixation (group E).

implanted, the head becomes prominent, and there is a risk of cartilage damage at the tibial head.

In the macroscopic investigation of the inserted pins, we could detect the obviously prominent heads and the location. Furthermore, the matrix could be matched with the location of the peak contact pressure detected by the sensor (Fig 5). From an engineering point of view, it is highly likely that high peak contact pressure occurs after tilted pin fixation.

In our study, on the one hand, we could detect significantly increased peak contact pressure after tilted implantation; on the other hand, we could also calculate a significantly increased difference in pressure between prominence and surrounding area. A very high difference in pressure correlates with a peaked prominence. Therefore, a high difference in pressure means high stress to the corresponding surface with potential damage to the cartilage or meniscal tissue.

Although we tried to countersink the pin heads in our experimental setup, we could not avoid prominent positioning of the pin heads in the 30° tilted group. This is probably caused by the material properties of the pins, which are stiff and porous.

Another interesting, not hypothesized result could be found. Even though mean peak contact pressure was significantly increased in the cartilage defect knees, both fixation strategies—conventional suturing and perpendicular pin fixation—significantly decreased the high forces. This effect has to be contributed to by the matrix that was inserted into the defect. The matrix seems to cover the defect and act as a spacer for the new cartilage. It is important to note that this result can only be discussed for the specific matrix used in this study (BioSeed C; BioTissue Technologies). This matrix consists of a 25 × 20 × 2-mm biodegradable polyglycolic acid scaffold that was

placed to cover the cartilage damage. Compared with other matrices used for m-ACI, this matrix is significantly thicker. This mechanism could be 1 reason for the clinical success of m-ACI procedures at time 0. Currently, there is no scientific evidence on the beneficial effect and percentages that can be contributed to the spacer effect or the cultivated cartilage cells in m-ACI.

In clinical practice: the arthroscopic pin fixation technique, as a minimally invasive technique, can minimize the disadvantages of the open chondral suture technique, such as adhesions, decreased range of motion, postoperative pain, and scar formation.¹⁹ Moreover, a recent biomechanical study has shown superior structural properties of the arthroscopic pin fixation technique in comparison to open suturing of the matrix.⁸

In the current literature there are many clinical studies about the outcome after ACI.^{2,4,11,14,17,18,22-26} Several randomized trials have been performed to compare clinical outcome after ACI versus microfracture or mosaicplasty treatment.

A previous randomized study by Knutsen et al.¹⁸ showed no significant difference in macroscopic (arthroscopic) or histologic results between ACI and microfracture on the femoral condyle and acceptable short-term clinical results. According to the results of the Short Form 36 physical component score 2 years postoperatively, the improvement in the microfracture group was significantly better than that in the ACI group. However, in this primary clinical outcome study, an open procedure (ACI) has been compared with an arthroscopic technique (microfracture).

Erggelet et al.²⁵ could show in their study that more than 26% of the side effects after open ACI are related to the arthrotomy, especially in the form of fibroarthrosis. Therefore the increased morbidity of the open

approach to the m-ACI fixation technique may interfere with the results. In a multicenter study of the clinical outcome after ACI, 26% of the procedure-related complications were associated with the open arthrotomy.²⁷

A recent systematic review reveals that no one technique for treatment of full-thickness articular cartilage defects in the knee produces superior clinical results.²⁸

Arthroscopic fixation of m-ACI may eliminate the interference of increased morbidity concerning the clinical results. In our hands, however, the arthroscopic fixation of a matrix is technically demanding. This applies to the arthroscopic pin fixation technique reported by Petersen et al.⁶ as well as the transosseous anchoring technique reported by Erggelet et al.¹⁹ A recent biomechanical study has shown that both fixation techniques have comparable excellent structural properties.⁸ Therefore the arthroscopic pin fixation technique seems to be an alternative for matrix fixation while performing m-ACI. Technically, challenges include accurate arthroscopic measuring of the defect and avoiding insertion of the pin at a tilted angle to the surface of the matrix.

The results of our study suggest significantly increased joint compression forces when the biodegradable pin is not inserted perpendicular to the surface. To avoid a tilted insertion, the surgeon needs to maintain the angle of the aiming device during drilling and insertion of the pin. In our experience, a good arthroscopic overview of the intra-articular aiming device and condyle surface and stable control of the knee flexion angle are the keys to a perpendicular insertion of the fixation pins.

Another option to avoid these reported complications could be a different design for fixation pins with a smaller head, different softer material, and a new arthroscopic device for facile intraosseous fixation of the matrix. To our knowledge, currently, there is no alternative product available for this requirement.

Future direction of m-ACI can only be speculated. In our opinion the arthroscopic approach to m-ACI is an important step to minimize the morbidity and probably further increase the clinical outcome. Other arthroscopic techniques are reported by using fibrin glue²⁹ or spheroids, which should stay at the surface by adhesion.³⁰ However, prospective clinical studies about the results of repair of chondral lesions using these techniques are missing.

A few limitations apply to this study. The study examines only the axial component of the joint forces. The lack of shear forces can probably affect the re-

sults. The healing process after m-ACI is also disregarded in the present test setup. In this study we used a porcine “in vitro model,” which may not have the same implications in comparison to an in vivo study in human knee joints. Although porcine knees are smaller than human specimens, our porcine knees obtained from the same aged pigs allow preconditioning for comparing testing of the influence on biomechanical behavior in a standardized model.

The most important parameter of our biomechanical testing is cartilage thickness. Adam et al.³¹ found a maximum and mean thickness of cartilage in human knees in elderly individuals of 3.8 mm and 1.9 mm. For a standardized animal model, larger animals with comparable cartilage thickness are necessary.³² Therefore we decided to choose a porcine model. Our specimens had a comparable cartilage thickness of a mean of 3.6 mm (± 0.71).^{31,33} In addition, we tested 1 specific matrix. The effects as reported in this study may be different from other matrices used for m-ACI techniques. In our study setup we tested just a limited range of tilted insertion with 30°. Correlation of peak contact pressure to the prominent head has been performed by macroscopic evaluation. We concluded from an engineer’s point of view that high peak contact pressure follows tilted pin fixation.

CONCLUSIONS

This study shows that after chondral suture and perpendicular pin fixation, there are no increased compression forces in the knee joint in comparison to an intact knee. Thirty degree tilted pin insertion contributes to increased joint compression forces.

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