Effect of graft positioning on dissipated energy in knee osteochondral autologous transplantation—A biomechanical study

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Abstract
Focal cartilage defects can be treated by osteochondral autologous transplantation (OAT). High congruence of the graft with the surrounding cartilage structure is essential for a good clinical outcome, but can not always be achieved. We recently established a method to measure dissipated energy (DE) as a friction parameter in knee joints. We now investigated how autograft harvesting and implant positioning affect the DE during knee motion. Six sheep knee joints were cyclically motioned under 400 N axial load. During the cyclic motion, the flexion angle and the respective torque were recorded and the DE was calculated. Several experimental conditions were tested: first, the DE was measured after approach had been performed (“native”). Subsequently, a cylinder was removed from the medial femur condyles and a donor cylinder was inserted from an unloaded site in four different transplant positions: even, 1 mm deeper, 1 mm higher, and flush without cartilage (defect). No significant changes in friction were observed between the native knee and an even or deep OAT positioning. We, however, found a small but significant increase in DE between the “native” and “1 mm high” formations (ΔDE compared with native = 14 mJ/cycle; P = .004 after data normalization) and a large increase in defect situation (ΔDE compared with native = 119 mJ/cycle; P = .001). Considering the long-term therapeutic aim that is pursued when performing OAT, elevated graft positioning should clearly be avoided. From a biomechanical point of view, donor site morbidity after cylinder harvest can be neglected.

KEYWORDS
cartilage repair, dissipated energy, friction, knee, osteochondral autologous transplantation

1 | INTRODUCTION

Focal cartilage lesions in the knee joint are often found in a young patient population of 20 to 40 years. These lesions can further propagate joint destruction and often lead to clinical symptoms such as pain or swelling. As such, they were found in 19% of patients who underwent diagnostic knee arthroscopy. The knee injury and osteoarthritis outcome score were developed to provide an adequate tool for people with high physical activity and to measure the outcome after cartilage repair therapy. The lesions mainly affect...
the medial femoral condyle (32%), followed by the patella (22%). Chondrocytes have a very low metabolic activity and lose their mitotic ability early in life. Thus, the cartilage has only a very limited capacity for self-repair. In case of traumatic cartilage injury surgical therapy is therefore often necessary.

Especially in small defects with possibly also subchondral pathology, osteochondral autologous transplantation (OAT) is the therapeutic option of choice. In contrast to bone marrow stimulating techniques and autologous chondrocyte transplantation it offers the advantage of a mature full-thickness cartilage transplant which is press-fit into the bone, allowing early mobilization and a high rate of return to sports and a superior level of athletic activity. Compared with bone marrow stimulating techniques like micro fracturing the therapeutic effect is of a longer nature thus making it more interesting especially for younger and active patients.

In OAT, a donor cylinder is harvested from a non-loaded hinge region and inserted snug into a female cylinder of similar size created at the cartilage defect site in the loading zone. An important requirement for a good clinical outcome is a high congruence of the graft with the surrounding cartilage structure, which can not always be achieved. Recent clinical studies indicated that an elevated graft of more than 1 mm is poorly tolerated.

Biomechanical studies in this area have so far been either limited to pressure measurements or to evaluation of the coefficient of friction, measured with a simple cable model dissecting all muscles and soft tissue. We have recently established and validated a method to measure dissipated energy (DE) as a friction parameter in knee joints with local cartilage defects. The key advantage of this model is that the measurements can be performed in complete joints thus ensuring experimental conditions resembling closely to the in-vivo situation without the need to extensively dissect the soft tissues.

The aim of the present study was to extend our model for characterizing cartilage defects to the measurement of OAT transplants. Furthermore we wanted to determine if harvesting of the donor cylinder already leads to an increase in DE. The key question of the current study was to investigate the effect of different types of OAT graft positioning using DE as an experimental outcome parameter. Based on the current recommendations, we measured DE for an even graft positioning and vertical malpositioning plus/minus one millimeter. From previous experiments with malreductioned tibial fractures (unpublished data) and previous studies with pressure measurements, we hypothesized that especially the upstanding graft would lead to increased friction in the joint.

2 | METHODS AND MATERIAL

2.1 | Specimens

Six fresh-frozen sheep knee joints were obtained post mortem and directly stored at −20°C. Prior to testing the joints were thawed overnight at room temperature wrapped in a cloth soaked with physiological saline solution. During preparation and testing, knee joints were additionally sprayed with saline solution from outside to prevent the soft tissue from dehydration.

2.2 | Robot

A robotic 6-degree-of-freedom setup (KUKA KR 60-3 robot, Augsburg, Germany; reproducibility, ±0.06 mm) including a universal force/torque sensor (ATI UFS, Theta SI1000-120; resolution, 0.25 N and 0.025 Nm) was used to perform axially loaded knee motion.

2.3 | Specimen preparation

Osteotomies of the femur and tibia were performed 20 cm above/below the joint space. At a distance of about 8 cm distal/proximal to the osteotomy, the bones were completely cleaned of periosteum, embedded in two-component resin (RenCast© FC 53 isocyanate/FC 53 polyol, Gößl & Pfaff GmbH, Karlskron, Germany) and fixed within aluminum cylinders in the robot. The settings of the robot, axes definition and recording of the passive path remained unchanged as described in previous studies.

Directly before the measurements, we performed a medial parapatellar approach to the knee joint and opened the capsule. The remaining synovial fluid was removed by rinsing and drying and instead NaCl 0.9% was distributed in the whole joint. Rinsing was repeated after each measurement to obtain uniform lubrication ratios throughout the whole measurement procedure and to eliminate dehydration effects as a possible confounder.

2.4 | Surgical treatment

The medial parapatellar approach was then closed by suture to prevent dehydration during the measurements and to obtain a soft tissue situation similar as after surgery. In addition, during each measurement, the knee joint was sprayed with NaCl solution and loosely wrapped with thin transparent film.

In the next step, recording of the individual passive flexion path was performed, which was required for further measurements. Axial compressive load of 400 N (approximate bodyweight of the sheep) was applied to the femur during the recording with cyclic flexion and extension. Subsequently, the first measurement of the DE was performed on the “native” knee. We then reopened the joint and with the receiver trephine (8 mm Aesculap AG, Tuttingen, Germany) a cylinder was created about 10 mm deep and 8 mm in diameter, in the main loading zone of the medial femoral condyle. Subsequently, an equivalent osteochondral graft was harvested from the same femoral condyle of an unloaded zone and introduced into the defect by the Osteochondral Autograft Transfer System (Aesculap AG, Tuttingen, Germany) (see Figure 1).
The osteochondral graft was inserted into the defect cylinder in four different conditions: first "even" (0 mm height difference), then "deep" (1 mm below the surrounding level), and finally "high" (1 mm above the surrounding level). These three conditions were randomized within the six specimens.

Simulating the wear of cartilage in an elevated graft position, we finally removed the cartilage of the cylinder implanted in the "high" condition with a surgical fraise ("defect"), so that the exposed bone and the surrounding cartilage were even (see Figure 2D).

To realize different graft positions, metal discs with a height of 0.5 mm were used at the bottom of the cylinder. To prevent sinking in of the graft, especially in the "high" and "defect" condition, a screw was inserted from the medial femur to support the base of the osteochondral graft. The head of the screw was sunk medially into the cortical bone to exclude a soft tissue irritation of the DE measurement. In order to subsequently remove the metal discs and the osteochondral graft, an additional, thinner hole from the base

FIGURE 1  Fixed knee joint in the robot (blue arrow) after a medial parapatellar approach. Extraction of the graft with the receiver trephine (red arrow) from an unloaded zone [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 2  A, flush graft position without a difference to the surrounding cartilage ("even"), B, recessed graft placement ("deep"), C, 1 mm elevated graft position with medial fixation screw ("high"), and D, flush graft position after cartilage resection ("defect") [Color figure can be viewed at wileyonlinelibrary.com]
of the transplantation site to the medial cortical bone was placed.

2.5 | Data analysis

The knee movement varies for ±10° about a flexion angle of approximately 60°. The axis of rotation varies with the vertical load, the defect grade, and the flexion angle. The intersegmental force and moment are functionally meaningful if they are defined at the “joint center” that lies on the axis of rotation. Therefore, the screw axis identification method was used to determine the instantaneous screw axis parameter for each displacement from position \( P_{Tm} P_{Tn} \) to \( B \) using the robot coordinates of the tool center point. The point on the helical axis and the unit vector of the helical axis with reference to \( P_n \) were then transformed back to Cartesian base coordinates. This was done for a complete cycle in flexion angle steps of 1°. The median helical axis defines the lateral axis of the new reference system. The wrench vectors consisting of the forces and moments at the base frame were transformed to the new reference frame. These calculations were done using an open-source robotics toolbox for MATLAB.

A low pass filter was used to plot the torque values of the force/torque sensor. Figure 3 shows the torque-time diagram and the corresponding hysteresis curve for the condition “high”. The dissipated energy is represented by the area within the hysteresis curve. The DE for one cycle is calculated with Formula (1).

\[
E_{\text{dis}} = \oint M \, d\phi
\]

(1)

\( E_{\text{dis}} \): dissipated energy
\( M \): torque
\( \phi \): flexion angle

Measurements were done for 20 cycles. The first two cycles were omitted in the calculation of the median DE per cycle. The integral was calculated using the Simpson integration rule from unfiltered torque values since the white noise compensates during integration and the median DE of 18 cycles was calculated for further analysis using SPSS-Statistics (IBM, Version 25.0.0.1).

3 | RESULTS

The experiments were completed for six specimens. The comparison of the DE in the native condition showed a high disparity between the individual specimens (Figure 4).

First, we asked if the measurement of the DE is also possible under OAT conditions and if the harvesting of the donor cylinder leads to a significant change of DE. Therefore, we compared the values obtained from the native knees (median [m] = 81.42 mJ/cycle, interquartile range [IQR] = 38.17; n = 6) with those in the
condition "even" (m = 88.79 mJ/cycle; IQR = 43.54; n = 6) after the first surgical procedure and after harvesting of the donor cylinder. In both conditions, we observed similar results (P > .999). Therefore we do not consider interfering factors, such as micro fragments or dehydration caused by the procedure to be of relevance. Harvesting the donor cylinder thus also does not appear to influence the DE in the knee joint.

Second, we investigated the effect of different types of graft positioning using DE as experimental outcome parameter. We thus analyzed and compared the DE for the conditions "native," "even," "deep," "high," and "defect" (Table 1). The DE of the five conditions was not normally distributed, as assessed by the Shapiro-Wilk test (P < .001). To compare the effects of different implant positions on DE, data were analyzed with the nonparametric Friedman’s test, where significant changes could be detected between the five conditions (native, even, high, deep, defect) (Friedman test χ²(4) = 20.400; P < .001; n = 6).

We then performed Dunn’s pairwise post-hoc tests and Bonferroni adjustments of the P-values on the basis of an alpha of .05. Significant differences were found between "native" and "defect" (P = .001; ΔDE = 119.38 mJ/cycle), as well as between "even" and "defect" (P = .010; ΔDE = 112.01 mJ/cycle). The effect sizes (r) were calculated using the formula \( r = z / \sqrt{n} \) (\( z \) = test statistic; \( n \) = number of pairs). A strong effect (r > 0.50) was found for "native" vs "defect" (r = 1.06) and "even" vs "defect" (r = .95).

To address the wide variation of values between the different knees in the "native" condition, the data were adjusted to their Median of the native condition. To this end, an adjustment factor \( k_N \) was calculated for each knee using the formula: \( k_N = 100 - m_{DE} \) (\( m_{DE} \) is median of 18 cycles in the condition "native"). For further calculations, the factor \( k_N \) was added to the median of each condition and each knee (Table 2).

When comparing the levels of DE between the three positioning conditions (even, deep, high) based on the adjusted data, a significant difference was observed across the groups (Friedman test \( \chi^2(2) = 10.33; P = .006; n = 6 \)) (see Figure 5). Again post-hoc analysis was performed with Dunn’s pairwise tests and Bonferroni adjustment was performed based on an alpha of .05. A significant difference was then found between the conditions "even" and "high" (P = .004; ΔDE = 14.09 mJ/cycle). When calculating the effect size (r) as described above, a strong effect (r > .50) was found for "even" vs "high" (r = 1.06).

### Table 1

| Condition | N | Minimum | Maximum | Median | Interquartile range |
|-----------|---|---------|---------|-------|---------------------|
| Native    | 6 | 48.43   | 110.75  | 81.42 | 38.17               |
| Even      | 6 | 53.63   | 123.41  | 88.79 | 43.54               |
| Deep      | 6 | 54.44   | 128.52  | 90.75 | 40.08               |
| High      | 6 | 57.51   | 135.50  | 102.05| 55.53               |
| Defect    | 6 | 99.54   | 347.08  | 200.80| 131.33               |

### Discussion

Our results indicate an enormous rise in friction in the flush graft position in the defect situation, where values for DE were almost three times higher (+165% compared with "native"). Likewise, the increase of DE in the condition "high" was still 22% when compared to "native." Only a small increase of 9% was found in the "deep" condition compared with "native."

In recent decades, pressure distribution in the joint had been the gold standard to evaluate the effects of graft positioning. The levels of DE registered in the present study are comparable to the pressure values obtained in other similar pressure distribution studies. In porcine knees, Koh et al, for example, reported a pressure increase...
of 57% in the 1 mm elevated graft position and of 11% in the 1 mm "deep" position when compared to the native knee. Similar results were also found by Latt et al\textsuperscript{10} when measuring pressure distribution in the human talus, where the condition "high" led to an increase of pressure and the condition "deep" to high pressures on the opposite facet of talus.

Over the past few years, in addition to pressure measurements, friction has also been established as an outcome parameter for OAT. Lane et al\textsuperscript{11}, for example, used a cable model on goat knee joints to calculate the coefficient of friction. In this setup, a load frame applies a constant load to the knee joint and moves it at a constant speed to simulate a physiological joint function. This technique does not reflect, however, that axial force and flexion velocity alter during stance and swing phases in a gait cycle. The actual 3D kinematics of sheep knees were described in detail by Taylor et al\textsuperscript{19} using bone pins, reflecting markers and an infrared optical measurement system. Therefore, in order to improve the measurement of friction and to adapt the experimental model to the physiological loads present during a gait cycle, we have recently developed in our laboratory a robot-based system with the possibility to measure DE as friction parameter.\textsuperscript{12} A key advantage of our system is the possibility to move each joint along its individual loading path with a spatiotemporally adjusted loading during the gait cycle and thus to minimize undesired and unnatural reactive forces. Further improvements were made when adapting the passive path to the detailed gait cycle described by Taylor et al\textsuperscript{24} Using discrete points of the passive flexion path to construct a complex knee flexion motion we now obtain an in vivo-like axial force profile with high reproducibility during the corresponding knee flexion.

Interestingly, when comparing the results of our study with those from the study of Lane et al, we describe a much smaller increase in friction after OAT in all conditions. For example Lane et al described an increase in coefficient of friction from "native" to "high" of about 300% while the increase in DE was only 22% in our study. While the outcome parameters "DE" and "coefficient of friction" are not completely comparable, we believe that this notable discrepancy can be well explained with the characteristics of the physiological gait cycle which we can better imitate with our applied technique: during the stance phase, high contact forces apply at a low flexion angle with no major change of this flexion angle. During the swing phase, however, the knee flexes without major contact forces. A combination of a large contact force and a fast alternation of the flexion angle does thus not occur in the physiological gait cycle. The high change of coefficient of friction could thus be exaggerated when compared to the physiological condition.

Another interesting result of our study is the similarity of the DE in the conditions "native" and "even." A main criticism of OAT is the high donor-site morbidity which occurs clinically in the form of patellofemoral disturbances, crepitation, knee stiffness, and persistent pain.\textsuperscript{20} Lane et al describe an increased friction by a factor of about 1.5 to 2 even in an "even" graft position resulting from the surgical procedure including donor-site morbidity.\textsuperscript{11} In our own study, we only observed an increase of DE from nativ to even of 8% without any statistical significance. We also attribute this minor difference in comparison to the results from Lane to the more physiological load protocol we applied. Our results may be an indication that the clinically reported symptoms are more likely caused by soft tissue irritation as a result of the surgical approach and scar formation rather

|       | Minimum | Maximum | Median | Interquartile range |
|-------|---------|---------|--------|---------------------|
| Even  | 98.75   | 112.66  | 106.18 | 6.45                |
| Deep  | 92.24   | 118.54  | 107.25 | 15.81               |
| High  | 105.97  | 128.40  | 120.27 | 14.98               |

*denotes a significant difference ($P < .05$) after Friedman’s group test with Dunn’s pairwise tests and Bonferroni adjustment [Color figure can be viewed at wileyonlinelibrary.com]
than biomechanical changes in the joint. This hypothesis is supported by the fact that the rate of donor-site morbidity does not correlate with the size and number of harvested grafts.\textsuperscript{20}

In a previous study investigating DE in OATs we used a planar joint model with a simple rotation movement of the two planar joint surfaces using carpometacarpal joints in a material testing machine.\textsuperscript{21} When comparing the results from both studies, a seeming contradiction in results can be noted with a decrease of DE in the condition 'high' when compared to "native. The applied experimental setup with a rotating joint surface over an upstanding fixed graft is, however, not comparable to the complex knee movement with anterior sliding and posterior rolling ("femoral roll-back mechanism"). The setup of two rotating planar joint surfaces is thus rather applicable to OATs repairing cartilage defects in the glenoid of the shoulder.\textsuperscript{22}

Unlike in most other studies, we performed additional testing of a condition termed "defect". The goal of this condition was to simulate a long-term effect of elevated graft position, were increased cartilage damage can be expected over time. It is already known that even in regular implanted grafts, a premature wear can be detected. In magnetic resonance imaging scans taken during OAT follow-up, an increased wear of cartilage could be detected 9 years after surgery.\textsuperscript{23} Increased T2-values of the grafts were also described when compared to the cartilage signal in the contralateral knees, a phenomenon that can be useful in predicting the development of radiological tibiofemoral osteoarthritis.\textsuperscript{24} This increased wear seems to be aggravated when having an elevated graft position, where an increased wear in shape of fibrillation, cartilage softening and fissuring of chondral tissue was observed in arthroscopic examinations.\textsuperscript{13} Elevated graft positioning was also associated with perigraft fissuring and fibroplasia, as well as subchondral cavitations when compared to flush implanted grafts in an in vivo sheep model 3 months after surgery.\textsuperscript{25}

In our experimental "defect" condition, we indeed found an enormous increase in DE caused by the rough bony surface of the graft. Such full-thickness destruction of the cartilage surface is likely to be rare under in-vivo conditions. But from the authors' point of view, this condition clarifies the potential long-term consequences of an elevated graft position in terms of friction within the joint.

It also needs to be pointed out that while the "high" condition can especially, in the long run, lead to cartilage destruction as mentioned above, the effects of friction for these biological changes remain unclear.

5 | CONCLUSION

With our experimental setup that closely imitated the physiological biomechanical conditions of the knee joint during the gait cycle we found no significant changes in friction between the native knee and an even or deep OAT positioning. From a biomechanical point of view, donor site morbidity after cylinder harvest can be neglected. Since the defect OAT situation led to a tremendous increase in DE, considering the long-term therapeutic aim that is pursued when performing OAT, elevated graft positioning should be clearly avoided.

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AUTHOR CONTRIBUTIONS

CW conceived the study, supervised the experiments and wrote the manuscript; DT performed the surgical procedures and experiments, AB and CJ wrote the robot application and helped with the statistical analyses; UKH helped with the statistical analysis and co-wrote the manuscript. All authors have read and approved the final submitted manuscript.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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