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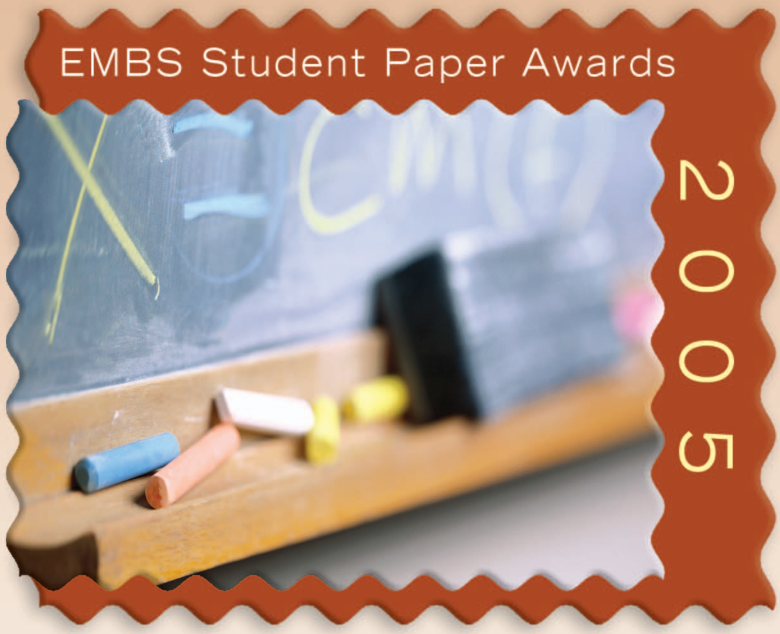

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Computer-Assisted Arthroplasty Using Bioengineered Autografts

Towards the Fast, Accurate Treatment of Joint Lesions

Recent advances in tissue-engineered cartilage open the door to new clinical treatments of joint lesions. Common to all therapies with in-vitro-engineered autografts is the need for optimal fit of the construct to allow screwless implantation and optimal integration into the live joint. Computer-assisted surgery (CAS) techniques are prime candidates to ensure the required accuracy, while at the same time simplifying the procedure. A pilot study has been conducted aiming at assembling a new set of methods to support ankle joint arthroplasty using bioengineered autografts. Computer assistance allows planning of the implant shape on a computed tomography (CT) image, manufacturing the construct according to the plan, and interoperatively navigating the surgical tools for implantation. A rotational symmetric model of the joint surface was used to avoid segmentation of the CT image; new software was developed to determine the joint axis and make the implant shape parameterizable. A complete cycle of treatment from planning to operation was conducted on a human cadaveric foot, thus proving the feasibility of computer-assisted arthroplasty using bioengineered autografts.

Introduction

Tissue-engineered articular cartilage has been a subject of research for a number of years (eg., [1], [2]). Although difficulties with cartilage structure and integration still persist, techniques based on combined grafts using cancellous bone and autologous cartilage are approaching clinical application [3]–[5].

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Using CAS technologies, the procedure can be significantly simplified and generalized to allow prefabrication of implant parts.

CAS techniques have the potential to ensure both the required accuracy and simplify the therapy. A pilot study was hence conducted, aiming at assembling a set of methods to realize and prove the feasibility of computer-assisted arthroplasty using bioengineered autografts. The ankle joint was chosen as a first target because of the lack of suitable alternatives: posttraumatic osteoarthritis can be diagnosed in patients as young as 20 years old, where classic therapies like total ankle joint arthroplasty using an artificial prosthesis or arthrodesis with fixation screws have considerable drawbacks (loss of mobility, poor long-term outcome expectation, difficult revision).

At the Universitätsklinikum Freiburg, Germany, one case of posttraumatic osteoarthritis has been treated with a bioengineered implant. The intervention was conducted in two steps: one for arthrotomy and defect molding and a second for implanting the bioengineered construct. Between the two operations, several weeks were needed to proliferate autologuous chondrocytes and integrate them into a cancellous bone construct shaped after the defect mold. Albeit clinically successful, this procedure does not lend itself well to routine application: the two-step operation, the long period of treatment, and the high-cost of individually constructed autografts make it a time-consuming and costly alternative to classical therapies. Using CAS technologies, the procedure can be significantly simplified and generalized to allow prefabrication of implant parts. The revised procedure consists of planning based on CT image data, harvesting mesenchymal stem cells by needle biopsy, constructing the autograft according to the planning, and conducting one single intervention for the arthrotomy and construct implantation. The defect debridement has to be accurate enough to fit the preconstructed graft; proving this accuracy in the context of a complete cycle of treatment was a main goal of this initial study.

Methods

Rotational Symmetric Ankle Joint Model

Based on the hingelike articulation of the upper ankle joint, a rotational symmetric joint was assumed in the region of interest for arthroplasty, allowing shape determination using a small number of points on the joint surface. A new software was developed to define the ankle joint shape model interactively on this basis. It consists of two steps: determine the joint axis and define the rotational profile. To determine the joint axis, arbitrary joint surface points are identified on sagittal planes in the region of interest. On each plane, the software performs a least-mean-square fitting of a circle to the points (Figure 1).

A second least-mean-square fit is performed in three-dimension (3-D) to find the optimal approximation of a line through all circle centers, which is used as the joint axis. The accuracy of this axis calculation depends on the number of points selected and on the anatomy of the individual joint. Selecting 40–80 surface points in a rotational symmetric region of the talus and/or tibia usually gives good results; in this study, about 100 points on the talus were used for talus grafts and about 100 points on the tibia for tibia grafts. Once the joint axis is established, a model for the joint follows in a straightforward way by rotating a joint profile around the axis.

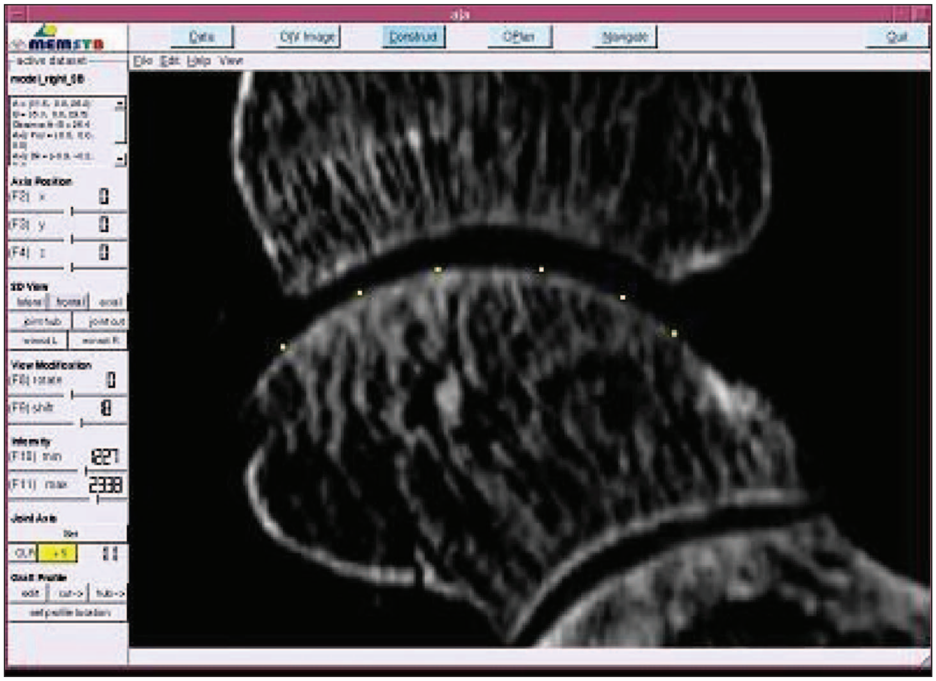


Fig. 1. Joint axis from joint surface points.

Preoperative Planning

The preoperative arthroplasty planning consists of four steps.

Determine the Joint Axis

As described in “Rotational Symmetric Ankle Joint Model,” arbitrary points are selected on sagittal planes in the region of interest. The software performs an optimal fit of a rotational symmetric body to the points selected to calculate the joint axis.

Determine the Lateral Graft Profile

A “hub view” is defined along the joint axis (Figure 2).

In this view, a “U” profile can be defined determining the front, bottom, and rear face of the implant. The hub view can be shifted along the joint axis to determine the optimal section of the joint to be replaced.

Determine the Frontal Graft Profile

A “cut view” is defined through the joint axis (Figure 3).

The axis is always shown horizontally, with the current view rotating around it. In this view, a profile can interactively be defined consisting of a “U” shape and a spline-interpolated curve following the joint surface. For further processing, the profile location is set at an arbitrary position to localize the U shape in 3-D.

Visualize the Resulting Construct Shape

Having defined the implant shape from hub view and from cut view, the visualization is done using the CAD software SolidWorks (SolidWorks Corporation, Concord, Massachusetts) as shown in Figure 4.

Construct Manufacturing

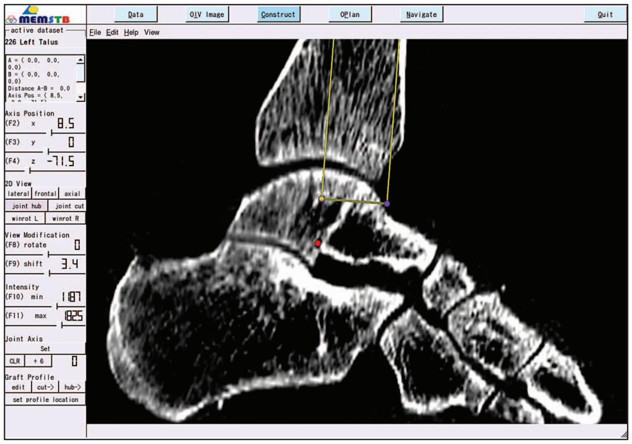
The CAD part description of the planned implant shape was used to program a CAM device to manufacture the dummy implant. The implants were custom milled according to this plan in PU plastic “ep-Dur” (Emaform AG, Gontenschwil, Switzerland). To improve the intraoperative flexibility, every implant was manufactured in two sizes: target size and target size minus 0.5 mm on the three faces relevant for press-fitting it. During operation, the appropriate size can be chosen according to the accuracy achieved.

Designing Tools for Arthrotomy

The first choice from the surgical point of view is an anterior access (avoiding osteotomy of the fibula) using a chisel. Tests have been carried out with angled chisels to study their behavior in human bone and the feasibility limits of possible construct shapes. Experiments on a human cadaver showed that angled or straight chisels are well suited for generating the planned defects; for the rear face of the defect, a milling device is required to achieve an optimal smoothness of the surface.

Preparing the CAS Environment

At our institute, a modular CAS platform has been developed that allows efficient and reusable implementation of applications for CAS. New algorithms and therapies can easily be tested and used in a variety of system configurations according to the requirements of collaborating clinics. This study was conducted using an active Optotrak optical tracking system from Northern Digital Inc., Waterloo, Ontario, Canada. Infrared markers were attached to the bone under treatment and to every surgical tool used. In-house image processing algorithms were used to establish the correspondence between bone, tools, and the visualized CT image (pair-point matching of landmarks on the bone, refining the result by matching arbitrary surface postoperative CT, hub view dimensions measured points). The planned implant shape and position were imported into the MEM Center CAS system. The contours of the implant were visualized in the CT image to allow navigated operation according to the plan.



active dataset
226 Left Talus

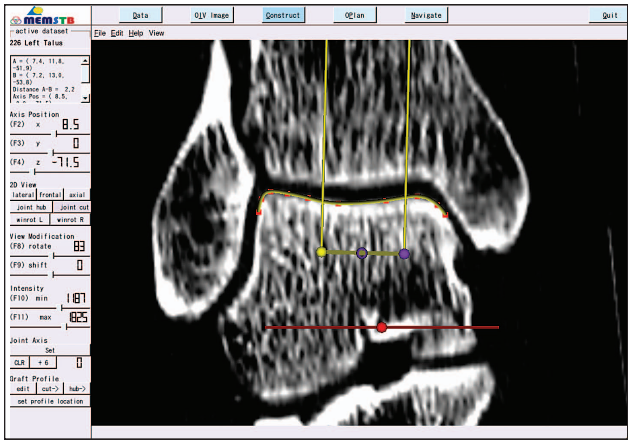
A = (0.0, 0.0, 0.0)
B = (0.0, 0.0, 0.0)
Distance A-B = 0.0
Axis Pos = (8.5,

Axis Position
(F2) x 8.5
(F3) y 0
(F4) z -71.5

View Modification
(F8) rotate 0
(F9) shift 3.4

Intensity
(F10) min 1187
(F11) max 1825

Fig. 2. Determining the lateral (“hub view”) profile.



active dataset
226 Left Talus

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B = (7.2, 13.0, -53.8)
Distance A-B = 2.2
Axis Pos = (8.5,

Axis Position
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(F3) y 0
(F4) z -71.5

View Modification
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(F9) shift 0

Intensity
(F10) min 1187
(F11) max 1825

Fig. 3. Determining the frontal (“cut view”) profile.

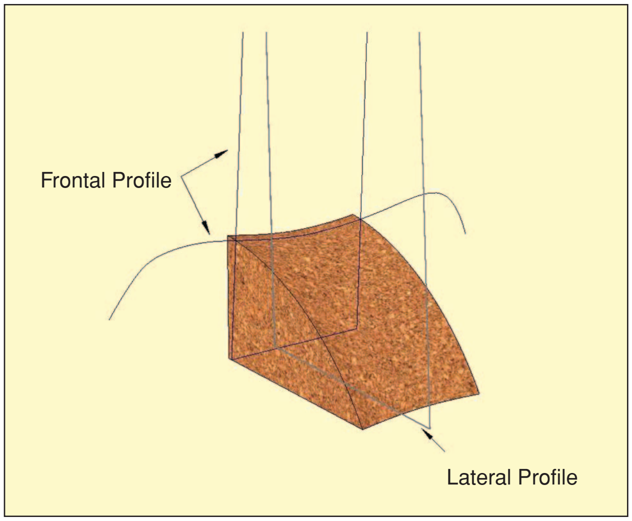
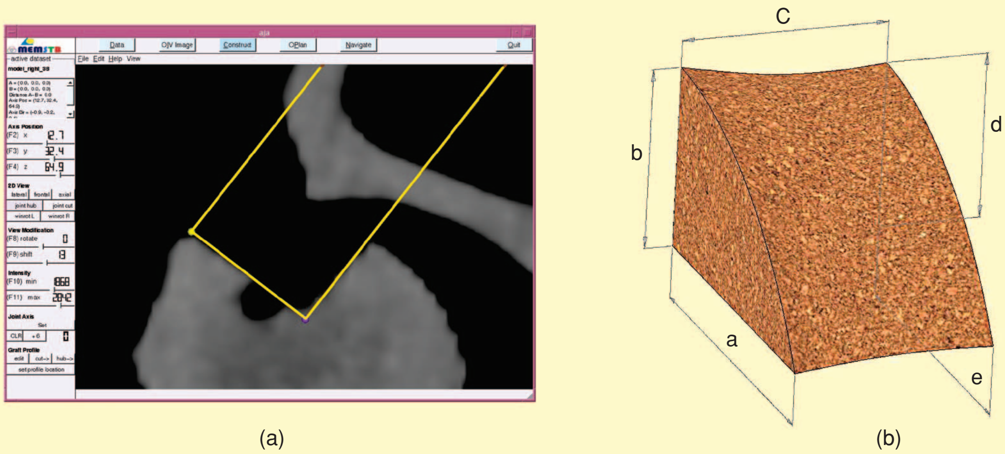


Fig. 4. The resulting implant shape visualized with SolidWorks.



(a)

(b)

Fig. 5. Postoperative analysis of the pretrial: (a) the postoperative CT, hub view, and (b) the dimensions measured.

Pretrial Using a Plastic Model

A first trial combining the main elements of the target therapy was made using a plastic foot model from 3B Scientific GmbH, Hamburg, Germany. One talar implant shape was planned based on a preoperative CT. The operation was conducted using the chisels and analyzed with postoperative CT. In the case of the trial with the plastic model, no dummy implant was manufactured. The defect was analyzed comparing distances on preoperative and postoperative CT images and doublechecking them with measures on the plastic model. They are shown in Figure 5 and listed in Table 1.

Accuracy analysis revealed an error displaying the implant shape, which affected the lateral face of the planned defect. Measurement of the other distances showed very encouraging results.

Table 1. Postoperative measurements of the pretrial operation.

Distance		Planned Value (mm)	Achieved Value (mm)	Error (mm)
a	Medial depth	14.58	14.10	0.48
b	Medial height	8.87	8.40	0.47
c	Rear width	15.45	15.20	0.35
d	Lateral height	11.02	9.50	1.52
e	Lateral depth	17.17	14.10	3.07

Table 2. Accuracy measurement using the postoperative CT image.

Distance		Planned Value (mm)	Achieved Value (mm)	Error (mm)
a	Medial depth	15.80	15.1	0.7
b	Medial height	9.64	9.5	0.1
c	Rear width	10.27	9.3	1.0
d	Lateral height	9.11	10.3	1.2
e	Lateral depth	15.26	16.4	1.1

Results

A trial operation was conducted on one cadaveric human foot. For the first time, a closed cycle of treatment was simulated from preoperative planning to implanting a custom graft shaped using the rotational symmetric model. A first intuitive result is how well the implant fits into the defect made. In the experiment, proper fixation of the graft was ensured by driving it into the defect using a hammer and pestle. Visual inspection showed a good restoration of the joint surface, with some locations where the bone had broken off due to the chiseling. Figures 6 and 7 document the results showing pre- and postoperative volumetric CT images of the operating sites. The same characteristic measurements were taken manually on those images as for the pretrial analysis. They are shown in Figure 5(b) and listed in Table 2. Live bone, being less brittle than cadaveric, can be expected to allow even better results.

The outcome was further analyzed using postoperative MRI imaging (Figure 8). Visual registration using landmarks visible in the CT volume was used to compare the pre- and postoperative MRI images. The dummy autograft, being manufactured in PU plastic, is not visible in the figure.

Discussion

As a proof of concept, the study showed that CAS techniques can successfully be applied to support ankle joint arthroplasty using bioengineered autografts. It is possible to make a custom-built bioimplant in a parameterizable shape planned on the basis of CT images and to implant it successfully at the planned site. The proof of this hypothesis was done assuming a rotational symmetric shape model of the ankle joint surface, which is only correct for a limited part of talus and tibia. A more general model could improve the matching of implant surface and surrounding joint surface, while at the same time making the technique applicable to other joints with different articulation. A big advantage of the rotational symmetric model is that no preoperative segmentation of the CT volume is required—a task which is difficult to achieve automatically, especially in joints with a narrow cavity. Manual segmentation is a very time-consuming alternative and would make the method impractical for clinical application. The determination of the ankle joint axis from the joint surface as developed in this project could be an interesting base for further studies: for example, the axis derived from the tibial or talar surface could be compared with each other or with the axis derived from the ankle movement and used for diagnosing pathologies. For that purpose, a closer investigation of its accuracy is required, which was not part of this study. No separation was made between different sources of error. The overall accuracy measured covers all aspects, from scanning a foot to implantation of a custom-made graft. A more detailed analysis, however, only makes sense if looking at specific aspects of the procedure; from a clinical perspective, the restoration of the joint surface is the only relevant result, provided the graft is properly fixed in the defect made. The cadaveric bone used in this study had a rather brittle characteristic and tended to break on chiseling edges. Clinical experience leads to the expectation that live bone will behave better in that respect; a systematic study of this fact has not been performed. This could also affect the choice of tools used for the intervention. In view of the rather small ankle joint, further optimization of the tools could also reduce the risk of damaging the untreated joint surface. The study used only one single cadaveric test to verify the feasibility of the target therapy. A spare construct was manufactured in PU plastic to accommodate for possible errors. This is sufficient as a proof of concept but not sufficient to allow the application of the therapy in clinical practice.

Future Work

The study described is a useful base for further development towards clinical use but also for studies in different directions. As mentioned in discussing the rotational symmetric joint model, studies on the axis of joints with hingelike articulation can be conducted using the software developed for ankle joint arthroplasty; a whole range of diagnostic and other applications could profit from joint axis determination. In cases where segmentation is practical, diagnosis could be supported by analyzing the differences between individual joint surfaces

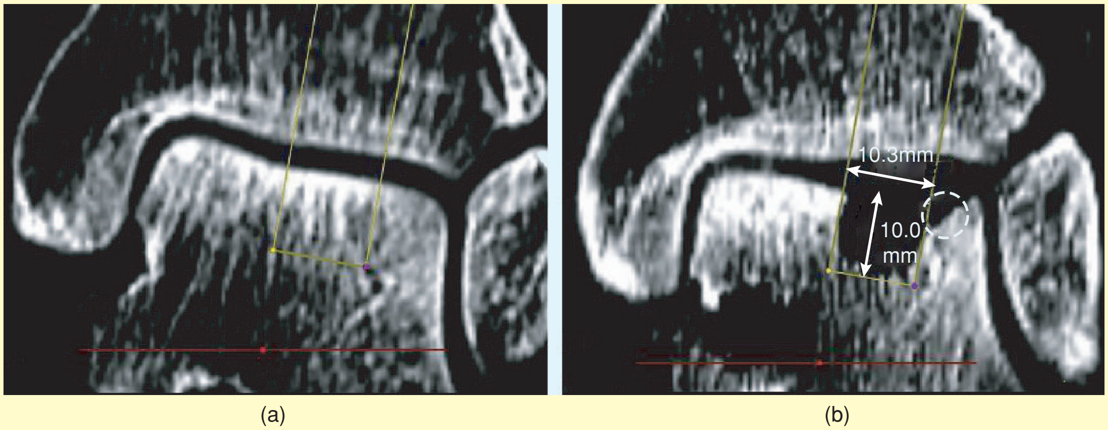


Fig. 6. The dorsal view of the operative result: (a) planned profile and (b) postoperative CT with damaged edge (encircled).

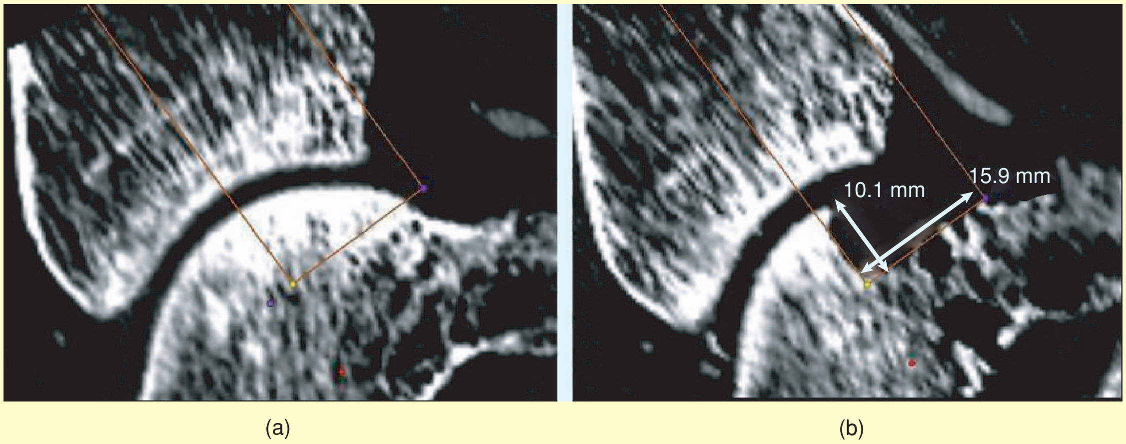


Fig. 7. Lateral view of the operative result: (a) the planned profile and (b) the postoperative CT.

A new software was developed to define the ankle joint shape model interactively.

and a parameterized joint model. As for arthroplasty using bioengineered autografts, our next steps focus on generalization and clinical applicability. Using statistical shape models ([6]) instead of a rotational symmetric one, the concept can be applied to any joint; verification on a series of cadaveric bones will finally pave the way to the clinic for a large number of bioengineered cartilage constructs.

Acknowledgments

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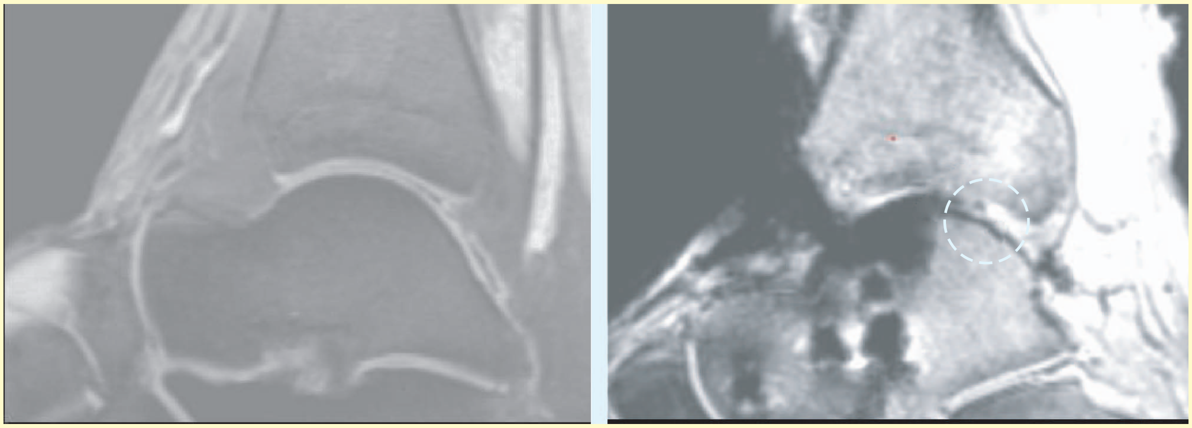
Rudolf Sidler graduated in 1989 with an M.Sc. in computer sciences from the Swiss Institute for Technology ETH, Zürich, Switzerland. After several years in telecommunications and the medical device industry, he joined the Maurice E. Müller Research Center for Orthopaedic Surgery, University of Bern, Switzerland, in 2003. He is currently a full time Ph.D. student in the Medical Imaging Group of the Institute for Surgical Technologies and Biomechanics, interested in application-oriented medical image processing and any kind of interdisciplinary projects.

Miguel Á. Gonzalez Ballester obtained his Ph.D. in 1999 from the University of Oxford, the United Kingdom, in the area of medical image analysis for neurological studies. He then worked for two years in Toshiba Medical Systems in Japan, doing research for their MRI Division. He then obtained a faculty position at the Epidaure Group in INRIA, France, where he worked on statistical methods for medical image analysis, until he moved to Switzerland in mid-2004. He is currently leading the Surgical Technology Division of the Institute for Surgical Technology, University of Bern, as well as heading the Medical Image Analysis Group.

Harald Marcel Bonél graduated in 1995 from medical school at the Technical University of Munich, Germany. He completed his residency at the Ludwig-Maximilians-University in Munich, Germany. After a research fellowship at the University of California in San Francisco in the field of musculoskeletal radiology, he became staff radiologist at the University of Bern, Switzerland. Currently, he is specializing in



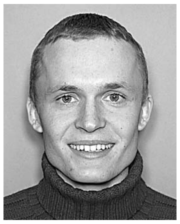
(a)

(b)

Fig. 8. The medial view of the operative result in MRI: (a) the preoperative MRI overview and (b) the postoperative MRI with cartilage damage.

musculoskeletal and women's imaging and is mainly pursuing research projects based on computed tomography and magnetic resonance imaging.

Martin Styner is a research assistant professor in the Department of Computer Science with a joint appointment in the Department of Psychiatry at the University of North Carolina at Chapel Hill (UNC). He received his master's degree in 1997 from Swiss Institute for Technology ETH, Zürich, Switzerland, and, subsequently, his Ph.D. in 2001 from UNC. His former positions include project leader at the Duke Image Analysis Laboratory, Duke University, and head of the Medical Image Analysis research group at the M.E. Müller Research Center, University of Bern, Switzerland. His main field of expertise is in medical image processing and analysis. He has an extensive background in anatomical structure and tissue segmentation, morphometry using shape analysis, modeling, and atlas building as well as intra- and intermodality registration.



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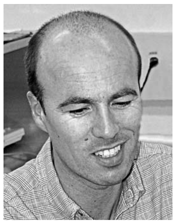
Norbert Paul Südkamp is a professor of trauma and reconstructive surgery and chairman of the Department of Orthopaedics and Traumatology at the Albert-Ludwigs-University Freiburg im Breisgau, Germany. In 1976, he received his first degree, an M.Sc. in electrical engineering, from the University of Hannover, Germany. It was followed by studies of medicine and a medical doctorate, received in 1982 from the Medical School, University of Hannover, Germany. Working as a trauma surgeon with various institutions in Germany, in 1988 he was awarded with a travel research grant from the German Trauma Society, leading him to the University of Mississippi at Jackson. Back in Germany, he became head surgeon in the Department of Trauma Surgery, Medical School Hannover, and in 1992, professor of trauma and reconstructive surgery as well as vice chair of the Department of Trauma Surgery of the University Clinic Charité in Berlin, Germany. Since 2001, he has been chair of the Department of Orthopaedics and Traumatology of the Albert-Ludwigs University in Freiburg im Breisgau, Germany. His research activities cover a broad spectrum of surgical procedures, technical aids, and bioengineering techniques in the field of trauma and reconstructive surgery. He also chairs the research board of the Association for the Study of Internal Fixation/Arbeitsgemeinschaft für Osteosynthesefragen (AO/ASIF) foundation.



Wolfgang Köstler graduated in 1988 as a medical doctor after studies at the Luwigs-Maximilians University and the Technical University in Munich, Germany. After his surgical education in Traunstein, Germany, he specialized in orthopedic and trauma surgery, working for clinics in Traunstein, Murnau, and the University of Freiburg, Germany. Currently, he is working as head of the department of trauma surgery in the community hospital in Lahr, Germany. His main research interests are in surgical navigation, joint injuries, and body repair mechanisms.

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