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Computer Assisted Orthopaedic Surgery With Image Based Individual Templates

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Recent developments in computer assisted surgery offer promising solutions for the translation of the high accuracy of the preoperative imaging and planning into precise intraoperative surgery. Broad clinical application is hindered by high costs, additional time during intervention, problems of intraoperative man and machine interaction, and the spatially constrained arrangement of additional equipment within the operating theater. An alternative technique for computerized tomographic image based preoperative three-dimensional planning and precise surgery on bone structures using individual templates has been developed. For the preoperative customization of these mechanical tool guides, a desktop computer controlled milling device is used as a three-dimensional printer to mold the shape of small reference areas of the bone surface automatically into the body of the template. Thus, the planned position and orientation of the tool guide in spatial relation to bone is stored in a structural way and can be reproduced intraoperatively by adjusting the position of the customized contact faces of the template until the location of exact fit to the bone is found. No additional computerized equipment or time is needed during surgery. The feasibility of this approach has been shown in spine, hip, and knee surgery, and it has been applied clinically for pelvic repositioning osteotomies in acetabular dysplasia therapy.

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Recent research activities in the area of computer assisted surgery have concentrated on the introduction of additional sensor and robot based guiding systems into the operating theater to enable adequate computer assisted transferral of the high accuracy of preoperative imaging and planning to precise surgery. Different promising solutions have been developed concerning the related problems of multimodal information processing and registration, safety and sensor concepts, and adequate control strategies.[5,19,22] Nevertheless, problems still remain such as the time needed intraoperatively for the interaction with additional technical system components, for the additional intraoperative registration of bone structures, the spatial arrangement of displays, sensors and robot systems within the operating room, the overall costs of the sensor or robot based systems, and mismatches regarding ergonomic design aspects of cognition and manual control.[17] An exact medical, technical, and ergonomic analysis is necessary to identify during which phases and sequences of intraoperative work additional guiding systems or even robotic assistance contributing a specific complementary function would be required.

In this context, the task sequences of different conventional orthopaedic interventions were investigated,[12,16] such as total hip and total knee replacement surgery being typical applications for computer assisted surgery systems.[9,19] One result of these investigations was that observable activities of direct orientation[6] only took approximately 2% to 4% of the overall operating time. If all activities are taken into account that have some connection with exact three-dimensional positioning, their share of total intervention time is approximately 10% to 15%.[12,16] Hence, the potential to shorten operating time and the related time slot for the introduction of computer assisted guiding systems seems to be limited. Prolongation of the operating time by additional intraoperative tasks and interactions with additional intraoperative equipment can be tolerated only to a limited degree because of medical, organizational, and economic reasons. In every case, it would have to be justified by significant enhancement of the therapeutic outcome. Moreover, the costs of additional equipment must be balanced against the requirement to deliver higher quality treatment to a larger number of patients.

The goal of the work described here was to develop a relatively simple, low cost solution that facilitates exact, safe, and fast implementation of planned surgery on bone structures, eliminates the need for continual radiographic monitoring, and avoids overburdening surgery with complex equipment and time consuming procedures.

PRINCIPLE OF INDIVIDUAL TEMPLATES

In orthopaedic surgery standard template systems are familiar technical means to guide drills and saws in total knee replacement. However, the design of these tool guides is based on averaged anatomic geometries. The positioning of the template on the bone bears no precise relationship to the position defined by individual preoperative planning.

Essentially, the missing information is the precise spatial correspondence between the individual bone structure in situ and the intended position of the tool guides.

The authors investigated a means of adding this missing information to the classic templates by providing shape based physical matching between the reference surface of the individual bone and the reference surface of the computer based model. This information is incorporated into an individual template.[12–16]

Individual templates are customized on the basis of three-dimensional reconstructions of the bone structures extracted from computerized tomographic (CT) image data in accordance with individual preoperative surgical planning. For preoperative customization, a low cost desktop milling machine is used as a three-dimensional printer to mold the shape of a small reference area on the individual bone automatically into the template. By this means the planned position and orientation of the tool guide in spatial relation to the bone is stored in a structural way and can be reproduced in situ adjusting the position of the contact faces of the template until they fit exactly on the bone (Fig 1). Neither iterative time consuming work under radiographic control or registration procedures, nor any additional computerized equipment is needed intraoperatively. Mechanical guides for drills, saws, chisels, or milling tools are adaptable or integrated into these individual templates in predefined positions for different types of interventions. Moreover, individual templates also can be used for fixation of a reference base for standard tool guides or other devices in a defined position on bone. The individual templates can be autoclaved and delivered to the operating room with the conventional instrument sets. The feasibility and adaptability of this approach has been shown on anatomic models and in cadaver tests

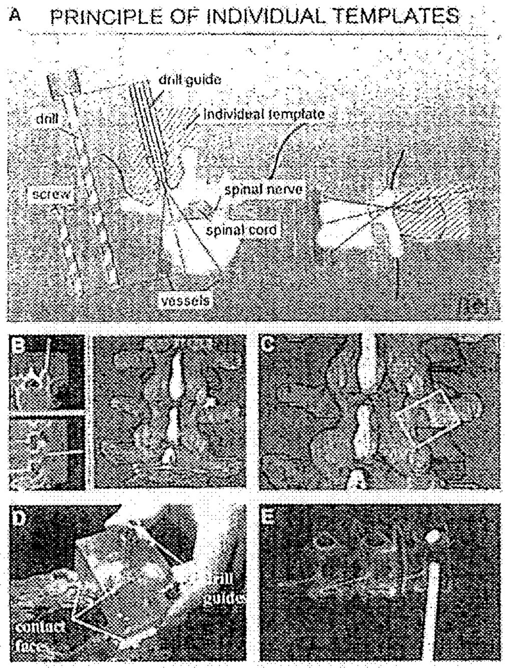

Fig 1. Pedicle screw placement: (A) the principle of individual templates based on preoperative CT imaging and computer based planning; (B) computer assisted planning of a pedicle screw placement with the DISOS planning system; (C) interactive specification of the reference contact face; (D) formclosed intraoperative fitting of the template; and (E) radiographic control of the placement of 5-mm rods in the pedicles without any perforation in situ.

for various applications.[10,14,16] Results of in vitro studies on accuracy have been reported in previous publications.[12,16]

Among the applications of this technique are pedicle screw placement (especially in scoliosis therapy; Fig 2); repositioning osteotomies in spine surgery; puncture of a cystic cavity in the femoral head; intertrochanteric repositioning osteotomy; initial reference osteotomies for total knee replacement (especially in the case of pathologic deformations); periacetabular repositioning osteotomies; open door decompression in the cervical spine; transcorporal decompression in the cervical spine; and decompression in the lumbal spine.

To depict the spectrum and potential of various implementations of the principle of individual templates, four typical examples will be described in more detail, with emphasis on the clinical application of triple repositioning osteotomies for the treatment of acetabular dysplasia.[12,14,18,20,22]

PEDICLE SCREW PLACEMENT

The selection of a pedicle screw of the appropriate length and caliber and its accurate fixation in the cortical bone of the pedicles and the vertebral body is essential for good anchoring. Perforations are the major specific complication of pedicle screw placements, implying a high risk of bone weakening or lesions of the spinal cord, nerve roots, or blood vessels.[3,7] To monitor the placement of the piloting Kirschner wire and finally the screw, as many as four to five radiographs in different planes are recommended per screw placement.[3] The authors selected this application for their initial investigations of the principle of individual templates[12,13] (Fig 1). Human anatomic specimens of lumbar spines were scanned with CT (slices 2–mm thick and 2–mm apart). The image data were transferred to the personal computer based DISOS planning workstation (Gemetec mbH, Aachen, Germany). Based on three-dimensional reconstructions automatically provided by the system, the surgeon selects an appropriate screw and defines its optimal placement (Fig 1B). The position and orientation of the related drill guide then is specified and can be incorporated into the individual template. To provide shape based intraoperative matching, small reference contact faces to the vertebral bone have to be specified on the display in the vicinity of the transverse process, the arch, or the spinous process. To this end, the surgeon interactively selects and positions an appropriate template within the three-dimensional view of the vertebral bone structure (Fig 1C). The surgeon is supported by the system, which automatically constrains the positioning to the direction of the defined bore axis and evaluates the quality of the contact

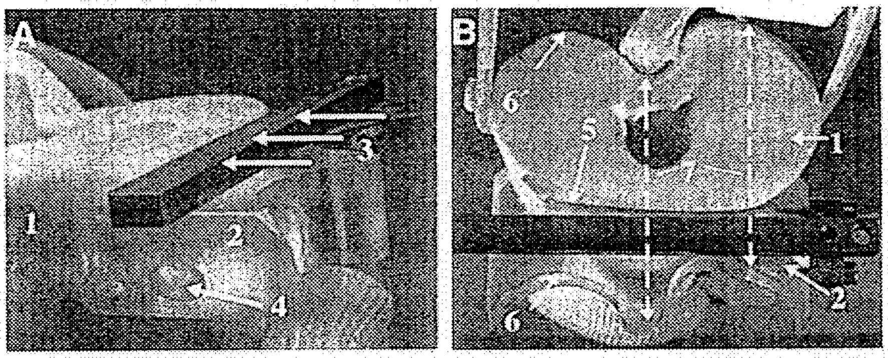

Fig 2A–B. Total knee arthroplasty: (A) laboratory investigation on a plastic bone model (1); individual template guiding the reference osteotomy (3) in tibial bone, optional fixation with a bone pin (4); (B) customized reference contact face (5) and copying profile (6) limiting cutting depth (7) to the dorsal contour (6) of tibial bone.

face. Afterward, the system automatically generates the manufacturing program and customizes the semifinished template with its integrated drilling guides. Intraoperatively, the defined position of the bore is reproduced by placing the self locating template where it fits exactly on the bone. Additionally, an optional radiographic control of the position of the stainless steel drilling guide is possible, because the plastic material of the template body is radiolucent. In two cadaver studies, in which one macerated specimen and one specimen with soft tissue were used, 5-mm bores have been reproduced exactly according to the preoperative planning without any perforation in situ.

TOTAL KNEE ARTHROPLASTY

In total knee arthroplasty accurate placement of implant components with respect to the individual mechanical axis of the leg is essential. Conventionally, modular mechanical devices corresponding to the intrinsic shape of the implant components are used to guide the osteotomies and bores for the preparation of the implant's seat. By mounting these conventional tool guide systems on an individual template as a basic customized reference, it is possible to reproduce the preoperatively planned position exactly even in the case of severely deformed bone. Moreover, for preservation of the posterior cruciate ligaments and the nerves and vessels in the hollow of the knee, not only the reference surface of the bone but also a copying surface limiting the cutting depth to the dorsal contour of the tibia can be molded into the template (Fig 2B). The geometry of the saw has to be known and a calibrated copying cam has to be mounted on the conventional saw.

Figure 2 shows a feasibility study with a CT image based individual template for the reference tibial cut for total knee replacement on a plastic bone model.[15] The geometry of the cut with its position, orientation, and limitations was planned on the basis of CT images (slices 2-mm thick and 2-mm apart). In addition, topograms could be used to identify the bone axis. A conventional saw guide can be mounted on the individual template, which serves as a reference base for subsequent work on the bone. The template has been customized in the areas of the reference surface and the individual copying profile corresponding to the dorsal contour of the tibial bone within the cut plane. The accuracy of the reproduction was measured directly on the bone model using a conventional precision goniometer and a caliper gauge. The predefined cut plane and the position of the copying profile limiting the cutting depth were reproduced with an accuracy better than 1 mm in all directions and 1° inclination in the sagittal and transverse planes.

OPEN DOOR DECOMPRESSION IN CERVICAL SPINE

The authors investigated the possibility of applying this principle to open door decompression in the cervical spine, which involves even more delicate constraints on the required accuracy of imaging, planning, and implementation.[14,15] The task is to mill away one side of the lamina completely and to preserve the anterior cortical layer on the other side, which acts as a hinge for the dorsal open door laminoplasty. Figure 3 shows a corresponding design of an individual template and the planning and intraoperative implementation in the framework of a cadaver study.[13,14] Applying the principle of copying profiles, a miniaturized copying cam corresponding to the geometry of the milling tool was mounted on a standard micromilling machine, with a sliding jig plate to guide the micromill perpendicular to the template. A bore with a defined depth was provided in the template for a final on site calibration of the length of the milling tool with respect to the copying cam. Then, both laminotomies were performed within less than 10 minutes, subsequently removing several layers of bone to less then 1 mm on the left side and approximately 1 mm on the right side. The micromilling tool was guided by the copying profile, leaving the anterior cortical hinge of the right lamina intact. It perforated only slightly at two points on the left side without damaging the dura (Fig 3E–F).

TRIPLE OSTEOTOMY OF PELVIC BONE FOR THE TREATMENT OF A DYSPLASTIC HIP JOINT

Periacetabular triple osteotomy for the treatment of hip dysplasia was chosen as the first exemplary clinical application of individual templates.[14,16,18] In acetabular dysplasia the task is to enlarge the weightbearing part of the acetabulum covering the femoral head to reduce the pressure on this area to physiologic limits. The major therapeutic goals are relief from pain and prevention of premature osteoarthrosis.

Using the operative procedure reported by Tönnis[20] and Tönnis and coworkers,[21] the acetabulum has to be mobilized by three osteotomies, which have to be performed in a defined position and orientation in relation to the acetabulum. If the distance from the acetabulum is too short there is a higher risk of avascular necrosis, and if the acetabular fragment becomes too large its free rotation may be impeded.[21] Moreover, the inclination of the cut planes influences the ability to rotate the fragment freely in a specific direction. Conventionally, the three osteotomies have to be performed under repeated radiographic control. The ischial osteotomy has to meet the obturator foramen and preserve the sciatic nerve and the sacral ligaments. Although the public osteotomy is less critical, it is directly adjacent to the femoral vein. For the manipulation and repositioning of the acetabulum, a Schanz screw has to be fixed on the acetabular fragment. The final iliac osteotomy has to meet the distal part of the incisura ischiadica. This is the longest and most difficult osteotomy and has the greatest influence on the mobility of the acetabular fragment and the initial stability of the fixation.

For the repositioning of the acetabulum, empiric standard values still are based on biplanar xray projections in the anteroposterior (AP) and faux profile planes. According to Tönnis et al[21] lateral center edge and anterior center edge angles of approximately 30° to 35° should be achieved. Additionally, three-dimensional CT imaging is recommended for diagnosis and surgical planning to achieve more accurate and reliable assessment of the individual anatomic and biomechanical conditions in the weightbearing area of the hip.[1,2,4,8,10] Nevertheless, the authors know of no validated standards based on three-dimensional imaging, comparable with the empiric data provided by Tönnis et

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