COMPUTER-INTEGRATED SURGERY

Technology and Clinical Applications

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THE MIT PRESS
CAMBRIDGE, MASSACHUSETTS
LONDON, ENGLAND

This book was set in Baskerville by Asco Trade Typesetting Ltd., Hong Kong and was printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data
Computer-integrated surgery : technology and clinical
applications / edited by Russell H. Taylor ... [et al.].
p. cm.
Includes bibliographical references and index.
ISBN 0-262-20097-X
1. Surgery—Data processing. 2. Surgery—Computer simulation. 3. Robot hands. I. Taylor, Russell H.
[DNLM: 1. Surgery, Operative—methods. 2. Computer Systems. 3. Man-Machine Systems. 4. Image Processing, Computer-Assisted. 5. Robotics. WO 500 C738 1995]
RD29.7.C65 1995
617.9′0285—dc20
DNLM/DLC
for Library of Congress 94-27743
CIP

33 Computer-Integrated Orthopaedic Surgery: Connection of Planning and Execution in Surgical Intervention

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Motivation

USING IMAGING devices such as x-ray CT and computer-based image-processing systems, it is possible to record structures of a living organism in slices and to realize 3D reconstructions that can be visualized on a color graphic monitor. Some 3D image-processing systems also permit 3D planning of surgical interventions. Intraoperatively, there often are problems of 3D orientation because there is no adequate technical aid for a consequent 3D transfer of the individually planned steps of intervention. The accuracy of execution depends uniquely on the experience, the ability to think in 3D on the basis of a mental 3D model, and the manual skillfulness of the surgeon. Depending on the anatomic location of the intervention, this can result in severe risks.

In general, only freehand-guided and -positioned instruments, 2D images (with a drawing of surgical planning), and intraoperative biplanar x-ray imaging devices are available. For some interventions, standard tool guides and templates exist. Intraoperative positioning of these tool guides and templates in spatial relation to bone structure is carried out freehand. Even with those special devices that are adjustable to the anatomic conditions, the position is not exactly defined by the preoperative planning. Intraoperative measurements and repeated alignment under x-ray control leads to an increased exposure to radiation for the medical staff as well as for the patient and it prolongs the duration of an intervention. Finally, it does not represent a sufficiently accurate and direct translation of the strategy of intervention defined during the preoperative phase of surgical planning. This situation may result, for example, in improper preparations of implant cavities in bone or imprecise osteotomies in the area of the extremities (Taylor et al., 1989). The precision and the high technologic standard of an individually designed implant is dramatically impaired by its freehand positioning during surgical intervention. For other even more complex and critical interventions such as those in the area of the spine or in pelvic surgery, no guide or positioning device is available.

Robots—the only technical answer?

For several years, international research activities have involved attempts to use modern robot technology with the aim of producing better tools and devices for quicker, more precise, and less straining surgical interventions. One major problem is the intraoperative localization and correlation among the reference systems of the object, the computer-based model, the environment, and the base of robot. To solve this problem of fusion (Taylor et al., 1989), different strategies and sensor concepts are pursued (Kosugi et al., 1988; Lavallée, 1989; Adams et al., 1990; Jacobi et al., 1990; Prasch et al., 1990; Martelli et al., 1991; Cinquin et al., 1992; Taylor et al., 1992). Furthermore, the problem of intraoperative human-machine interaction (HMI) as well as the security and reliability of the overall system are central problems to be solved before robotics can be introduced into the surgical process (Rau and Trispel, 1982; Taylor et al., 1989).

The use of the technical system as such should require only a minimum of attention from the surgeon. The critical work process of surgical intervention within the physician-patient-machine system should not be charged additionally by time-consuming complex interactions with technical system components. This could be avoided by system integration effected through an ergonomic system design approach. By transferring the interaction with the complex technical system into a preoperative preparation and planning phase, the medical staff can be relieved of avoidable tasks during operation. The results of preoperative preparation and planning must be stored in a way that can be used easily during intervention.

Nevertheless, the special aspects of an ergonomic design of a medical work system, with its general as well as individual marginal conditions, have to be taken into account. Technical training of medical staff is possible only to a limited extend. The introduction of a robotic system into the operating theater probably will require an operating assistant with a special technical education. Apart from additional costs, this possibility leads to an additional human system component with additional interfaces and the necessity of interactions (human-human and human-machine) during surgical intervention. The number of interfaces (especially those between human and machine or human and human, respectively) always increases complexity, need of communication, and probability of error within a work system (Bernotat and Rau, 1980; Rau and Trispel, 1982). The design of efficient user interfaces with self-explanatory user guidance and optimized interaction sequences is one of the most important challenges in CIS.

The surgeon as the responsible medical expert must remain the highest hierarchic instance of the overall system. He or she must have total control of the process and must be able, even as a nontechnical user, to intervene at any moment in the ongoing process. At the same time, the surgeon wants to use the accuracy and precision (and, in very few cases, the speed) of the robot.

Safety and reliability of the system must be ensured by redundant sensor and control systems. Concerning intrinsic safety of the system, Davies et al. (1992) propose a very interesting concept of mechanically constraining the degrees of freedom and adapting the individual kinematic form of the motion axes to the specific task. Motion, in this case, is physically restricted to the limits of the planned work area. This concept would require different robots for different surgical interventions, which certainly would prevent a broad clinical application. A modular concept with multiple interchangeable subunits might be a solution to this problem, but this would lead to decreased accuracy. Another possibility is to use a robot with independent and redundant degrees of freedom and to brake or block mechanically the axes that are not needed for the specific mission or during different phases of intervention, respectively.

The analysis of surgical tasks and the synthesis and design of a kinematic configuration useful for a wide variety of surgical interventions will be essential for further work. Additionally, it should be mentioned that even very sophisticated preoperative simulations of an intervention will not prevent the need for an intraoperative change or modification of positioning or strategy in some cases. The intraoperative on-line modification and verification of a robot program will be very difficult for the medical staff. However, functionality on a lower level must be provided in some way. The surgeon should be able to use, but should not be forced to be absolutely dependent on, the technical support in any phase of intervention.

In summary, the use of robots in the operating room must be limited to interventions involving very complex 3D work through narrow accesses or that could not be realized without robotic support. In this context it should be noted that robots, on the one hand, and servomanipulators or remote manipulators, on the other, should be clearly distinguished from 6D coordinate-measuring devices (medical localizing systems) (Kosugi et al. 1988; Adams et al., 1990) or even automatic medical retractor holder systems that use auxiliary energy for locking mechanisms (McEwen et al., 1989). A *robot* is an automatic motion apparatus with several axes of which the movements are independently programmable and possibly sensor-guided with respect to sequences of movement, paths, or angles (Desoyer, Kopacek, and Troch, 1985). They are equipped with grippers, tools, or devices to perform positioning, handling, or manufacturing missions. Servomanipulators or remote manipulators are position- or force-controlled "passive robots" that are guided by the human operator (master). Areas of movement and restricted areas of collision could be programmed before operation and translated into variations of mechanical impedances in each degree of freedom depending on position, speed, or reacting forces. Regarding medical robotics, the different specifications should be clearly taken into account and compared with the specific requirements of each medical application.

Computer-integrated advanced orthopaedics

The aim of computer-integrated advanced orthopaedics (CIAO) is to enable medical staff to execute surgical interventions on bone according to the preoperative planning. The enhancement of precision and accuracy, shorter execution times, and additional technical support must not be traded for an additional loading of the intraoperative work process by complex technical systems or interactions (figure 33.1). The time for intraoperative measurement and alignment is minimized through a shift of these tasks into the preoperative planning phase. Work under x-ray control or with robotic systems is not necessary in most cases.

Nevertheless it should be possible to use a robot or servomanipulator as an intraoperative tool for geometrically difficult performances. In particular, the problem of a suitable user interface for the interaction of a nontechnical user with a complex technical system is one topic of our work. We try to avoid additional stress on the patient by avoiding, for example, preoperative (even invasive) fixation of reference markers or frames.

The central functional element in our approach is an individual template designed on the basis of preoperative CT image data. This individual template has so-called contact faces that copy without undercutting the complementary shape of segments of bone surface intraoperatively reachable by the surgeon. Hence, the template can be intraoperatively placed form-closed on the bone surface in exactly the predefined position and orientation. The region of bone structure relevant for surgical planning is scanned using x-ray CT. The 3D reconstruction and planning of intervention is performed by the physician using the 3D image-processing system DISOS (Desktop Image-processing System for Orthopedic Surgery) developed especially within the CIAO project (figure 33.2). The results of segmentation of bone structure geometries and of surgical planning are documented in standard ASCII files.

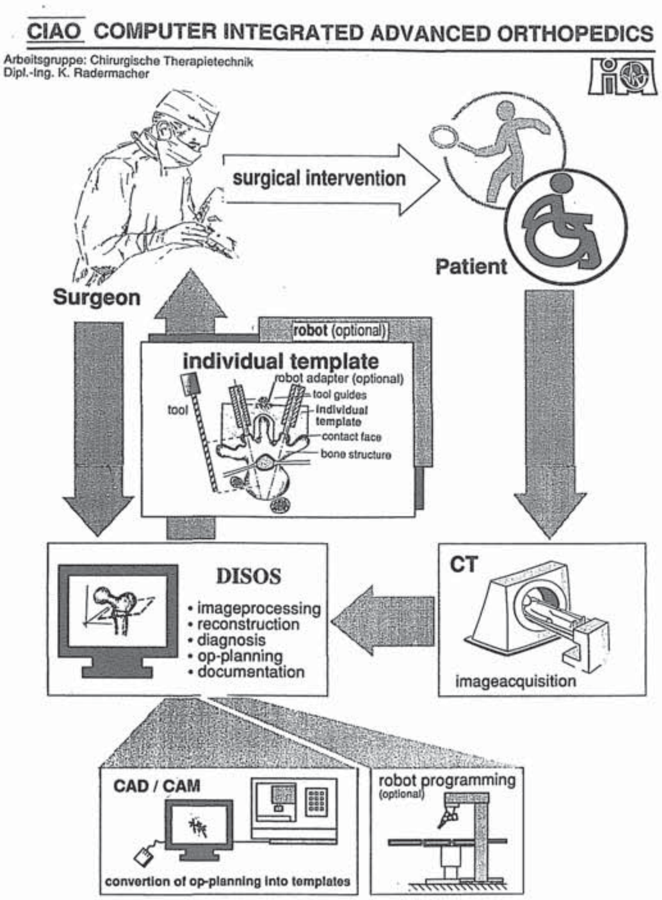

FIGURE 33.1 The concept of CIAO. (Reprinted with permission from Radermacher et al., 1993.)

DISOS is implemented on standard IBM PC hardware and is ergonomically designed especially with respect to the surgeon as a nontechnical user. An intuitive color, graphic user interface and an on-line help system allow the medical staff to perform diagnosis, image processing, and planning of surgical intervention without the need for any additional explanation or manual. It should allow maximum use of the medical expert's knowledge during diagnosis, segmentation, region of interest selection, correction of artifacts, verification of 3D reconstruction, and surgical planning of intervention. The data transmitted by DISOS contain, among other items, all necessary information about contours and surfaces of bony struc-

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