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Brief Report

Experimental Robotic Milling in Skull-Base Surgery

Philipp A. Federspil, M.D., Beate Plinkert, M.D., and Peter K. Plinkert, M.D., Ph.D.
University of Saarland, Department of Oto-Rhino-Laryngology, Homburg, Germany

ABSTRACT

Objective: In the field of otorhinolaryngology, a variety of skull implants have been developed to assist hearing-impaired or even deaf patients. The first step in the implantation procedure, and also in lateral skull-base surgery, is to drill the calvarian or mastoid bone. We intended to investigate the hitherto unknown parameters for performing this procedure and to establish the first set-up for robotic milling of the lateral skull base.

Materials and Methods: Experimental milling of the skull base was conducted on two human specimens using a hexapod robot.

Results: Optimized parameters were determined with a drill speed of 30,000 revolutions/min and a form feed rate of 5 mm/s for the calvarium and 1 mm/s for mastoid bone, respectively, in a spiral-path fashion. While using a cutting burr, mean force levels were 4.81 N for calvarian bone and 6.12 N for mastoid bone, respectively—well below our empirical limit of 10 N. However, maximum levels easily surpassed these limits, reaching 27.7 N.

Conclusion: The prerequisites for robotic skull-base surgery were fulfilled. With further work to implement feedback of sensory input, robots may increase precision for various tasks in skull-base surgery. Comp Aid Surg 8:42–48 (2003). ©2003 CAS Journal, LLC

Key words: **robot, implant, mastoid, mastoidectomy, otolaryngology surgery, drill, burr**
Key link: **http://www.uniklinik-saarland.de/hno/forschung.htm**

OBJECTIVE

Due to their ability to work tirelessly with extremely high precision and to control the quality of the process, robots have dominated certain aspects of industrial production for some time, and have subsequently entered the medical field. The term robot is used for any type of electromechanical device designed to move surgical tools. More precisely, such devices may be divided into manipulators and robots. While manipulators are only able to translate the surgeon's movements into those of the surgeon's tool (e.g., an endoscope, cutter, etc.),[1,2] a robot is able to perform surgery after preoperative free programming. Today, surgical robots are routinely used to assist in small but important steps, such as drilling femoral cavities for total hip replacement endoprostheses with extreme precision and accuracy (e.g., ROBODOC®, Integrated Surgical Systems, Davis, CA).[3] To date, more than 40 systems have entered clinical practice.

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Address correspondence/reprint requests to: Dr. Philipp A. Federspil, Klinik und Poliklinik für Hals-Nasen-Ohrenheilkunde, Universitätskliniken des Saarlandes, Kirrberger Strasse, D-66421 Homburg (Saar), Germany. Telephone: +49 6841 1622984; Fax: +49 6841 1622997; E-mail: Ph.Federspil@uniklinik-saarland.de; http://www.hno-homburg.de

Part of this research was previously presented at the Computer Assisted Radiology and Surgery (CARS 2001) meeting in Berlin, June 2001.

Other manipulators and robot systems, like CASPAR® (Computer Assisted Surgical Planning And Robotics) or Evolution 1®, are listed in Table 1. Some of them are still being evaluated under experimental conditions, but others, like Evolution I®, are already being applied for neuroendoscopy in humans.[4] The main core of the Evolution I® robot is the parallel kinematic of the hexapod with 6 degrees of freedom. Because of its extreme precision, load, and stiffness, it was first applied in astronomy and flight simulators.[4,5] Another "interactive" robot system, OTTO®, was developed in the Surgical Robotics Laboratory, Charité, Berlin. It is based on the SurgiScope (Elekta / joyumarie®) and is used for implantation of catheters in brachytherapy or titanium screws for craniofacial prostheses.[6] Drilling is performed by the surgeon himself, but the robot records the position and angle of the surgical instruments. OTTO® is a supporting system to guide and move surgical tools, and can also restrict the surgeon's area of action to protect adjacent critical structures like nerves or vessels. Unlike Evolution 1® or CASPAR®, OTTO® is not able to perform independent invasive operations with free programming.

During the last decade, a revolutionary development took place in otorhinolaryngology surgery, providing numerous patients with implantable hearing devices to restore hearing (cochlear implants or TICA®).[7] For the implantation procedure, it is necessary to locate the main module in the calvarium and to open and prepare the mastoid process with a burr in a retro-auricular fashion to insert the electrodes (for a cochlear implant)[8] or the coupling elements to the auditory ossicles (for implantable hearing aids)[9] (Fig. 1). This type of operation requires the surgeon to undertake heavy drilling on the one hand and precise microsurgical work on the other (Table 2).

The objective of this study was to investigate hitherto unknown parameters for performing the procedure, establish the first set-up for robotic milling of the skull base, and thereby determine the basis for robot-controlled milling of an implant bed for the above-mentioned implants.

MATERIALS AND METHODS

Two complete human formaldehyde-fixed specimens were positioned on a mobile operating table (Blancomed Inc., Germany) with the head fixed in a Mayfield clamp. These specimens were taken from cadavers donated with informed consent prior to death. Milling was performed with the Microtron EC system (Aesculap, Inc., Tuttlingen, Germany), which offers the option for different speeds ranging from 15,000 to 40,000 revolutions/min, and includes an integrated cooling system.

Forces were measured with FTS3751/322104 (Schunk Inc., Germany). The measurement is achieved with a semiconductor lengthening meter between the base and the flange.

Temperature was measured with a non-contact infrared-based thermo-sensor (Omega Inc., Germany), with focus distance 152 mm, focus diameter 3.9 mm, accuracy ±1% of the value or

Table 1. Overview of Commercially Available Manipulators and Robots

Systems	Type	Producer	Applications
ROBODOC	robot	Integrated Surgical Systems ISS (Davis, CA)	hip and knee prostheses
CASPAR	robot	Developed by ortoMAQUET, now distributed by Universal Robot Systems (URS) (Schwerin and Rastatt, Germany)	hip and knee prostheses
OTTO	robot	SurgiScope, joyumarie (Germany)	oral and extraoral implantation, application system for brachytherapy
Evolution 1	robot	Universal Robot Systems (URS) (Schwerin, Germany)	neuroendoscopy
AESOP	manipulator	ComputerMotion (Goleta, USA)	active endoscope positioner, e.g., in laparoscopy
EndoAssist	manipulator	Armstrong Healthcare (UK)	active endoscope positioner, e.g., in laparoscopy
NeuroMate	manipulator	ISS	endoscope positioner in neurosurgery
ZEUS	manipulator	ComputerMotion (Goleta, USA)	endoscope positioner and guiding system for surgical instruments, e.g., in laparoscopic cholecystectomy or mitral valve surgery
Da Vinci	manipulator	Intuitive Surgical (Mountain View, CA, USA)	endoscope positioner and guiding system for surgical instruments, e.g., in laparoscopic cholecystectomy or mitral valve surgery

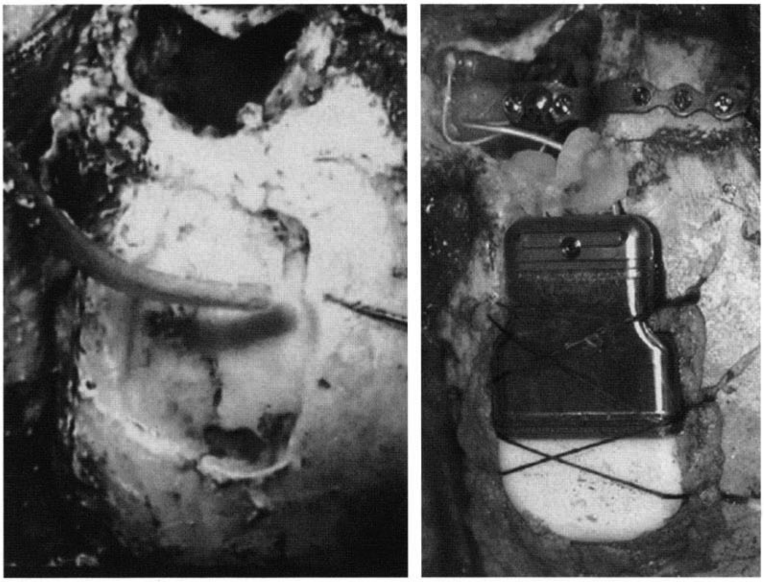

Fig. 1. Implantation of a TICA implantable hearing device (Leysieffer-Zenner, formerly marketed by Implex Inc.).[7] a) A manually milled implant cavity in the lateral skull base. b) The main module of the implant fitted into the cavity.

±3°C, and range of measurement −18°C to 538°C. During the experiments, adjustment of the sensor was undertaken with an additional laser pointer. This was fixed coaxially on the optic of the senor and the chosen focus could be adjusted to the measurement axes. The distance was then determined and adjusted. The sample frequency was 1 Hz.

Measurement of vibrations and acceleration was based on a piezoelectric crystal (KS943 Metra Mess- und Frequenztechnik, MMF Radebeul, Germany). With the current kept constant, voltage deviations indicated the appearance of accelerations. The sensor was fixed on the calvarium bone with titanium screws. Data were transferred to the computer via three coaxial lines and three corresponding channels (corresponding to the three axes of measurement).

The robot is based on the hexapod kinematic of an industrial robot (Physik Instrumente, Inc., Waldbronn, Germany), as modified at the Fraunhofer IPA (Stuttgart, Germany), and marketed with further modifications by the URS company (Schwerin, Germany) under the name Evolution 1®.[4,5]

In setting up a model for skull-base surgery, we chose milling of an implant bed (e.g., for implantable hearing devices) and mastoidectomy. The following aspects were examined:

1. Measurement of the following parameters:
   - temperature
   - force and momentum
   - vibrations and acceleration
2. Determination of optimized parameters for milling:
   - form feed rates
   - drill speed (revolutions per second)
   - depth of penetration
   - path parameters with different burrs (meander, spiral)
   - variations of bony tissue (mastoid, calvarium)
3. Correlation with histological tissue effects

Table 2. Reasons for Using Robots in Lateral Skull-base Surgery

1. Good approach to the operating area
2. Operation can be planned using preoperative CT scans
3. Reproducibility on the day of operation
4. Discrepant ergonomics during implantation of hearing systems or cochlea implants
5. Necessity for precision due to adjacent critical structures
6. Increasing case numbers are forecast in the future

4. Controlling for quality and security of the process:
    - prevention of heat necrosis
    - head (and robot) fixation

Experiments

In preliminary experiments, we determined the optimal position of the sensors and established limits for temperature, force, vibration, and acceleration in manual drilling (Table 4). We then performed 4 different serial tests on two specimens. These were as follows:

1. Different revolutions were tested while form feed rates were kept constant.
2. Variations of form feed rates were tested with constant optimal revolution (as determined from the results of the first experiment).
3. Optimal results from experiments 1 and 2 were combined to test two different milling patterns (meander and spiral).
4. Macroscopic and histological examination of the bone surface was conducted after milling with optimal path, form feed rate, and revolutions, but with different burrs (size and material, e.g., cutting burr or diamond burr).

The settings for the different experiments were recorded (Table 3A), and the results were documented, analyzed (Table 3B) and demonstrated graphically in diagrams (Fig. 2). In more than 130 individual experiments, we examined different combinations of revolutions, form feed rates, milling patterns, burr shapes (cutting burr, diamond burr—spherical or cubic) and burr sizes (1.5–4.0-mm burr head), as well as different ways of fixing the specimens to the robot.

RESULTS

Determination of Limits

The absolute limits for force, momentum, temperature, acceleration, or vibration in manual or robotic drilling procedures are still unknown. To determine these, it is necessary to interfere with the investigational material, which is not feasible in real surgery for ethical reasons. We postulated that values measured during in-vivo milling in conventional surgery were suitable for setting limits.

First, we determined the limits for force and momentum during several experiments with manual drilling on anatomic specimens in the ENT laboratory (Table 4). Limits for temperature in vital bone are known from the experimental studies of Fuchsberger.[10] As only indirect values were known for comparing acceleration and vibration values, it was necessary to perform several measurements during a routine in-vivo cochlear implantation to obtain reliable values for acceleration and vibration.

Results of the Serial Tests

The values measured in the serial tests were listed, analyzed, and compared with the limit values (Table 5). By measuring the parameters of force, momentum, acceleration, and vibration in

Table 3A. Examples of Two Individual Experiments

Serial test no.	Revolutions/ min	Form feed rate (mm/s)	Depth of penetration (mm)	Path	Type of burr
Specimen 1					
59	10,000	3	0.5	meander	cutting burr ∅ 2.5 mm
60	10,000	5	0.5	square, straight line	cutting burr ∅ 2.5 mm

Table 3B. Results of the Individual Experiments

	Force (N)				Momentum (Nm)				Acceleration (m/s^2)				Δ temp. (°C)
No.	Max. comp. + F	Max. comp. − F	Max. $F_{Res.}$	Mean $F_{Res.}$	Max. comp. + M	Max. comp. − M	Max. $M_{Res.}$	Mean $M_{Res.}$	Max. comp. + acc.	Max. comp. − acc.	Max. $acc._{Res.}$	Mean $acc._{Res.}$	Max. average temp. (+13°)
59	y	z	13.9	3.52	z	z	1.4	0.31	z	z	1.43	0.21	10.1
60	z	x	21.02	5.04	y	z	2.21	0.37	z	z	1.88	0.19	23.6

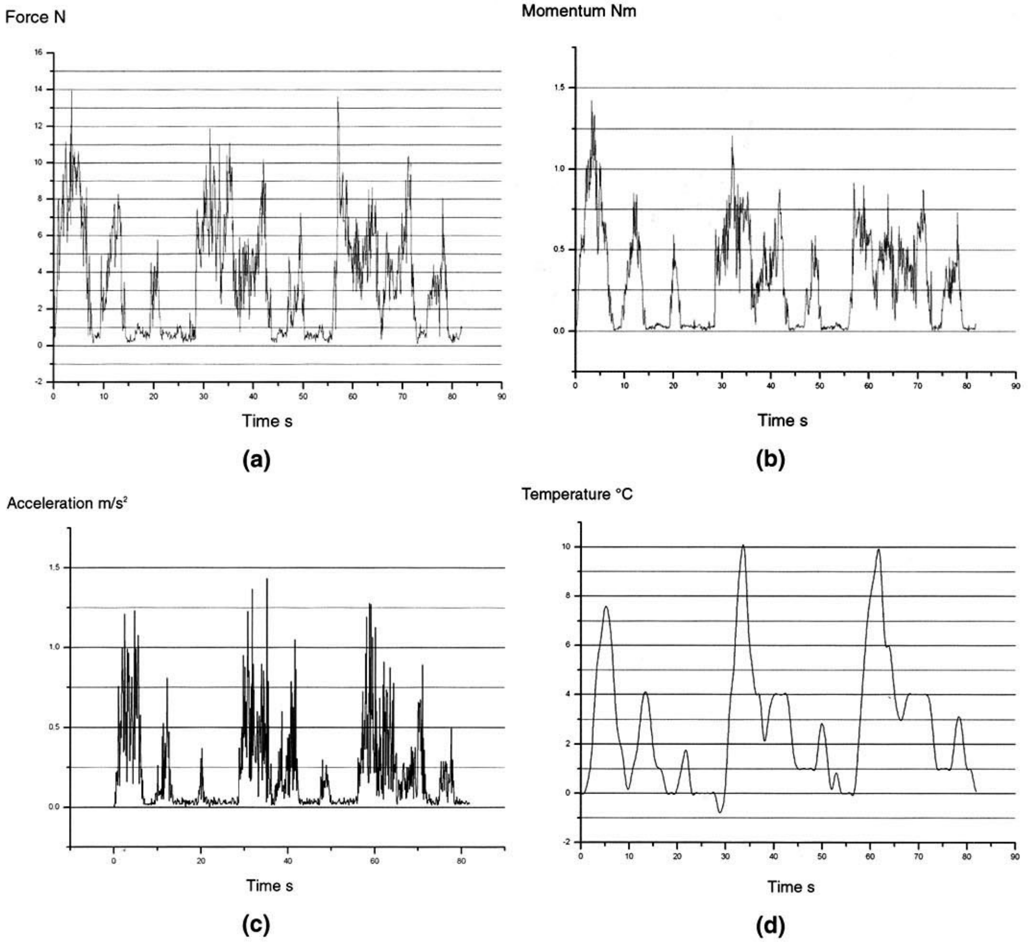

Fig. 2. The results of each experiment were listed and documented in diagrams, as shown in these examples for the single experiment No. 59. Measured results for force, momentum, acceleration, and temperature are demonstrated dependent to the milling period while drilling a meander pattern with 10,000 revolutions/min and a form feed rate of 3 mm/s using a cutting burr (Ø 2.5 mm).

comparison to these limits, optimal milling parameters were ascertained (Table 6).

Histological Diagnosis

For evaluation of heat-induced injuries in the tissues, and to determine differences in these due to the use of different burrs, two specimens (calvarium or mastoid) were examined histologically. Both showed pathologies in the form of vacuolation and changes in the shape or nuclei of the cells, as well as distinct eosinophilia of the cytoplasm. These histological changes reached a depth

Table 4. Limits for Robot-Controlled Milling in the Lateral Skull Base

Parameter	Limit	Reference
Force, F_{max} (N)	10 (mastoid)	For manual milling at the calvarium or mastoid
Momentum, M_{max} (Nm)	0.68 (mastoid)	M_{res}
Acceleration, A_{max} (m/s^2)	~10 (single amplitude)	In-vivo measurements from the preliminary experiments
Temperature, T_{max} (°C)	60°C	Ref. 10

Table 5. Comparison of the Parameter Values Measured in the Serial Tests on Two Specimens With Optimal Milling Parameters for Revolution Range and Patterns

	Parameter	Type	Mean/maximum/limit	Remarks
			Calvarium: v = 5 mm/s, 30,000 U/min	
1	force (N)	a	4.81/27.74*/10	Experiments performed with the cutting burr. Mean values are below limits, but maximums exceed limits noticeably.
2	force (N)	b	6.12/14.53*/10	
3	momentum (Nm)	a	0.35/1.89*/0.68	
4	momentum (Nm)	b	0.42/1.38*/0.68	
			Mastoid: v = 1 mm/s, 30,000 U/min	
1	force (N)	a	3.61/13.15*# 1.99/10.47*⊕ /10	Experiments performed with cutting burr and diamond burr. Mean values are below limits, but maximums exceed limits noticeably.
2	force (N)	b	3.92/13.1*# 2.47/10.47*⊕ 10	
3	momentum (Nm)	a	0.2/0.93*# 0.17/0.79*⊕ 0.68	
4	momentum (Nm)	b	0.23/0.77*# 0.13/0.50*⊕ 0.68	
*average for specimen 1 + 2, # = cutting burr, ⊕ = diamond burr				
			All experiments	
5	acceleration (m/s^2)	a	–/2.74/10	All values are below limit value.
6	acceleration (m/s^2)	b	–/0.92/10	
7	Δtemp. (°C)	a	–/53.34°/60°C (based on room temp. of 25°C)	While measuring room temp. of 25°C, we detected a max. of 53.32°C, which is below the limit. Condition is a sufficient cooling system.
8	Δtemp. (°C)	b	–	No results.

a = Mean of the maximum under a vary of different revolutions, patterns, and paths over all milling experiments with a defined starting period and a number of runs-through.

b = Mean of the maximum under a vary of different revolutions, patterns, and paths, but with a discrete run-through.

Note: Differences between the values can be attributed to sudden bone contact or loss while milling in discrete paths.

of 0.75 mm with both the diamond and cutting burrs. They are not specific, but are usually caused by heat and are comparable to those observed with manual milling.

DISCUSSION

The analysis shows that the average force and momentum levels during milling with the robot are settled below those encountered in manual milling. However, the *maximum* force values temporarily exceeded the set limits by a significant margin, while the values for temperature and vibration remained below the limits. Histological observation confirmed these results. With temperature increasing by a factor of 2.4 while milling without cooling, the effectiveness of a functioning

Table 6. Optimal Milling Parameters and General Remarks

- For quick work with low force and momentum, analysis of 300 individual results show the preferred form feed rate to be v = 5 mm/s at 30,000 U/m for the calotte and v = 1 mm/s at 30,000 U/min for the mastoid (Table 5).
- When milling under these optimal parameters, there are no significant differences in the results for the calotte and mastoid.
- Because of the even temperature pattern, the spiral path, with a low temperature maximum, is preferable to a meander path in the mastoid.
- Average forces and momentum during milling with the robot settled below the forces encountered during manual milling. However, the maximum forces are (partly) noticeably above the mentioned limits.
- While milling specimen 2, force and momentum are similar, but acceleration values are greater than those in specimen 1 by a factor of 2.
- Values for temperature (rinse) and acceleration are below the limits.
- When milling without rinse, the mean temperature increases by a factor of 2.4.
- By choosing a distance between paths ≤0.5 ∅ of the cutting burr, the milling surface is almost a flat plane and is without grooves.
- Increasing the diameter of the cutting burrs led to a parallel increase in the forces and momentum by a factor of 1.5–2.5. Maximum forces of 22.3 N are measured with a cone-shaping cutting burr.
- Forces and momentum increase with ascending form feed rates on the z-axes.
- An additional fixation of the head is correlated with increasing acceleration values by a factor of 1.5 while milling the calvarium, and by a factor of 3 for the mastoid.

cooling system is clearly shown. The standard rinse system used in this study was able to fulfill the cooling requirement sufficiently. However, any deficiency in this regard risks sudden overheating. Sufficient control of temperature was only selective, due especially to the different depths of invasiveness, so a redundant cooling system should be used.

The above-mentioned parameters are acceptable for planning a robot-controlled mastoidectomy or an implantation bed for a cochlear implant. However, the cause and influence of the observed maximal forces should be analyzed further. The experiments demonstrated an influence for milling parameters because of non-calculable aspects like room temperature, quality of the burr surface, fixation of the specimen, etc., which are also important for the precision of milling with a robot. To avoid these extreme values, it seems preferable to modulate the method or implement the milling with a multi-sensorial control for parameters like force, milling pattern, temperature, vibration, etc., resulting in a greater chance for extreme precision and simultaneously providing additional security for the patient.

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