European Archives of Oto-Rhino-Laryngology (2019) 276:63–70
https://doi.org/10.1007/s00405-018-5194-y

OTOLOGY

Three-dimensional force analysis of surgical manipulations at the long process of the incus

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Received: 27 September 2018 / Accepted: 1 November 2018 / Published online: 8 November 2018
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Abstract

Purpose Surgical manipulation with application of inappropriate force may damage middle ear structures leading to hearing loss. This work analyzes the forces applied in simulated otosurgical exercises in a laboratory set-up by measuring the spatial components of applied forces with objective assessment criteria. With these criteria, the individual force characteristics applied by the surgeon can be quantified and an objective feedback can be given about their surgical maneuvers.

Methods A natural size model of the human incus was mounted on a load cell to measure the spatial forces in all three directions during different manipulation tasks performed under the microscope by ten surgeons from our department having different levels of experience in otosurgery. The motions of the incus model and the instrument tip were recorded simultaneously with a video camera.

Results Independent of surgical experience, a three-dimensional force pattern could be detected with components transverse to the desired force directions. The measured forces applied by trainees showed larger variations in magnitude, in spatial distribution and in temporal course than those applied by experienced surgeons. A better repeatability of identical tasks, constancy of force patterns and low peak force values could be seen in the group of experienced surgeons.

Conclusions The laboratory system presented in this study using simultaneous video and 3-D force registration allows the objective assessment of surgical manipulations, e.g., at the long process of the incus. Training with video and force feedback provides information about surgical techniques and skill development of surgeons and has the potential to shorten the learning curve and to diminish intra-operative risks to patients.

Keywords Otosurgery · Ear ossicles spatial force measurement · Trainees · Training · Exercises

Introduction

Forces transmitted to the middle ear ossicles, e.g., during surgery can cause mechanical damage with conductive hearing loss. There are only few data available on force characteristics of surgical manipulations in otosurgery. This pilot work analyzed the forces applied in simulated otosurgical exercises in a laboratory set-up based on objective assessment criteria. The measured force characteristics together with the optical observation were recorded. These measurements reflect the surgeons´ capabilities and surgical skills and allow an objective feedback for the surgeon. Furthermore, we present a practice tool using video and 3-D force registration for trainees in otosurgery.

Part of the data was presented at the 85th Congress of the German Society of Otorhinolaryngology and Head & Neck Surgery, Dortmund, Germany, 2014. https://doi.org/10.3205/14hnod445.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00405-018-5194-y) contains supplementary material, which is available to authorized users.

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Materials and methods

Test rig for measurements

We constructed a test rig with a natural size brass model of the human incus to measure forces applied during different manipulation tasks. The incus was elastically suspended according to the compliance of the natural ossicular chain. The motions of the incus model and the instrument tip were recorded simultaneously with a high-definition video camera (DNT DigiMicro 2.0 Scale) oriented along the axis of the model (Fig. 1). A load cell (Kyowa LSM-B-10NSA1) was used to measure all three components of the spatially oriented force applied by the surgeon to the long process of the incus. The three signals were amplified (HBM MC 55 B). The system was calibrated with standard test weights before each measurement session.

Test persons

Ten surgeons from our department having different levels of experience in otosurgery took part in this study. Two of the surgeons had 30 years (H.W.P.) and 18 years (H.E.B.) of otosurgical experience having completed more than 6000 and 2000 otosurgical procedures, respectively. The eight less experienced surgeons had minimal (less than 100 otosurgical procedures) or no otosurgical experience. All test persons used a forceps (catalog number: 227401, Storz, Germany), and performed basic manipulations of otosurgery called tasks ("push", "pull", "pull and hold") in defined spatial directions under the microscope. The test persons were required to perform all movements with visible displacement of the incus model, but with moderate force.

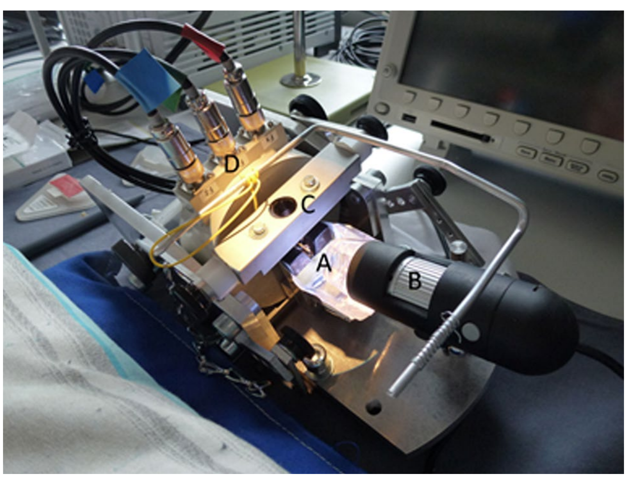

Fig. 1 Measurement set-up without microscope. **a** Model of long process of the incus. **b** Video camera. **c** Model for the outer ear canal. **d** 3-D load cell

Definition of tasks representing typical manipulations in otosurgery

Five different test sequences were defined (S1 to S5) (Table 1; Figs. 2a–d, 3). Test persons had to grasp the long process of the incus with the forceps and move it gently in prescribed directions. The sequence S1 consists of two cycles: in the first cycle the tasks are two repeated movements carried out in the posterior direction (toward the mastoid), and in the second cycle the tasks are two movements to be carried out in the anterior direction (toward the patient`s face) as shown in Fig. 2a (Table 1). The sequence S2 shown in Fig. 2b was similar to sequence S1 but in the medial direction (toward the promontorium) and in the lateral direction (toward the outer ear canal, i.e., toward the surgeon). The sequence S3 shown in Fig. 2c was analogous in the superior (cranial) and inferior (caudal) directions. Furthermore, a fourth sequence S4 was defined as a tonic/static exercise in which the long process of the incus had to be pulled laterally and held for 10 s (Fig. 2d). Sequence S5 was a simulation of a crimping process: the surgeon had to grasp the long process of the incus again and press it with the forceps to simulate the process of crimping a stapes prosthesis. An example measurement of a crimping process can be seen in the video as Electronic Supplementary Material.

Criteria of analysis

The force patterns measured were analyzed and characterized with regard to the following criteria. From the mechanical point of view, force is a vector, defined by its magnitude and orientation, therefore, peak force amplitude, mean force, and direction were calculated. Moreover, force has a

Table 1 Definition of tasks of the study

Sequence S1		Sequence S2		Sequence S3		Sequence S4	Sequence S5
First cycle	Second cycle	First cycle	Second cycle	First cycle	Second cycle		
2 × task posterior movement	2 × task anterior movement	2 × task medial movement	2 × task lateral movement	2 × task superior movement	2 × task inferior movement	1 task pulling lateral and hold	1 task simulation of crimping

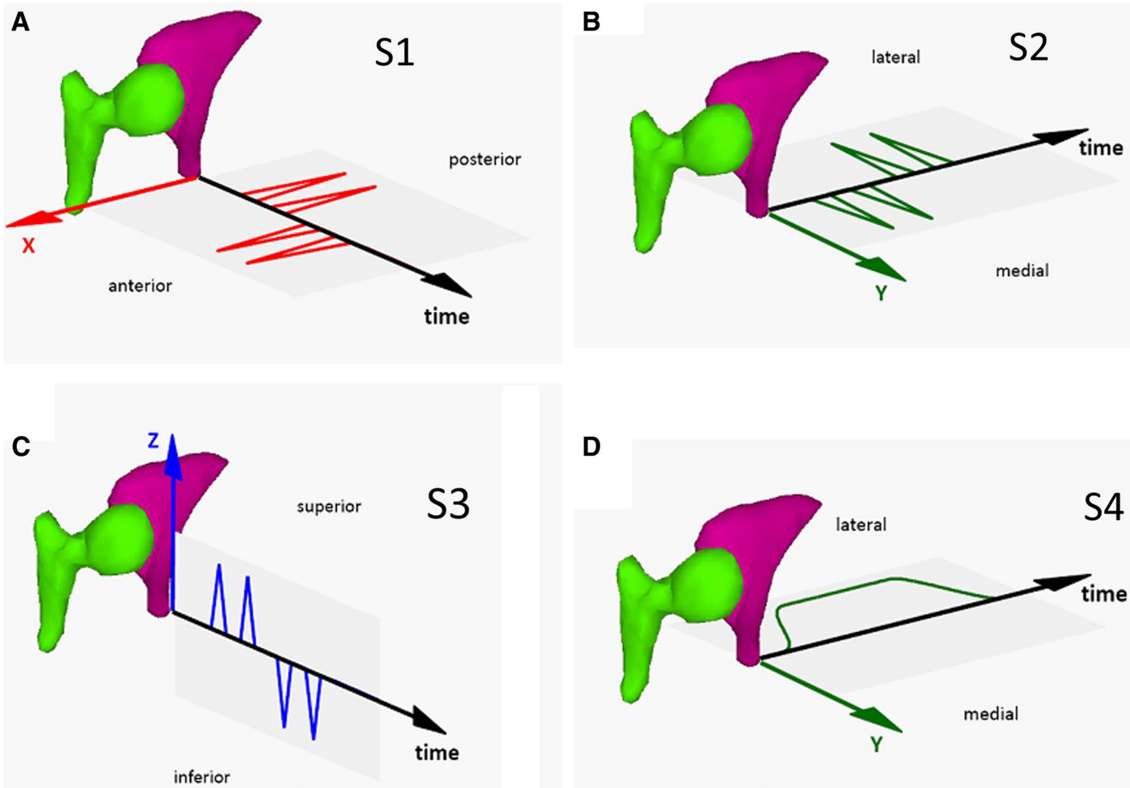

Fig. 2 **a**–**d** Definitions of directions of different manipulations in the three specific directions. The colors indicate the different directions in the coordinate system used: *x* in red, *y* in green, and *z* in blue. **a** Test sequence S1—manipulation toward nuchal (posterior) and patient's face (anterior), i.e. in *x*-axis, red lines. **b** Test sequence S2—manipulation in the direction of the promontorium (medial) and toward the outer ear canal (lateral), perpendicular to the stapes footplate, i.e., in *y*-axis, green lines. **c** Test sequence S3—manipulation toward the top of patient's head (superior) and in the direction of the patient's body (inferior), i.e. in *z*-axis, blue lines. **d** Test sequence S4—manipulation "pull and hold" laterally toward the outer ear canal in *y*-axis, green line

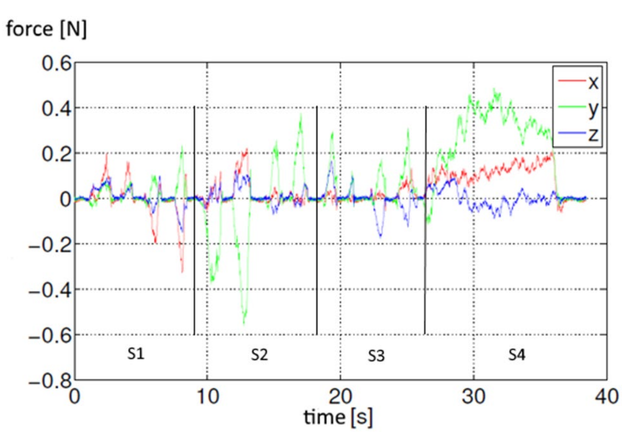

Fig. 3 An example of spatial force components over time for the test sequences S1 to S4 carried out by a trainee. Red line: force component in *x*-direction (anterior = positive, posterior = negative). Green line: force component in *y*-direction (lateral = positive, medial = negative). Blue line: force component in *z*-direction (superior = positive, inferior = negative)

spatial and temporal course, hence, constancy of force level, constancy of force direction (isotropy), and repeatability of tasks within a cycle were evaluated. Furthermore, the control of the instrument by the test persons was assessed by looking at the deviations of magnitude and force directions of the desired task.

Results

Different force patterns have been detected during the measurements:

1. Three-dimensional force patterns were obvious even in one-directional tasks S1 to S4. There were also significant force components transverse to the desired force directions (Figs. 3, 4, 5).
2. Distinct peak values were detected in the force signals during tasks S2 in the *y*-axis ("push medial"/"pull lateral"), which is perpendicular to the stapes footplate, i.e., the axis of the surgical instrument. The maximum

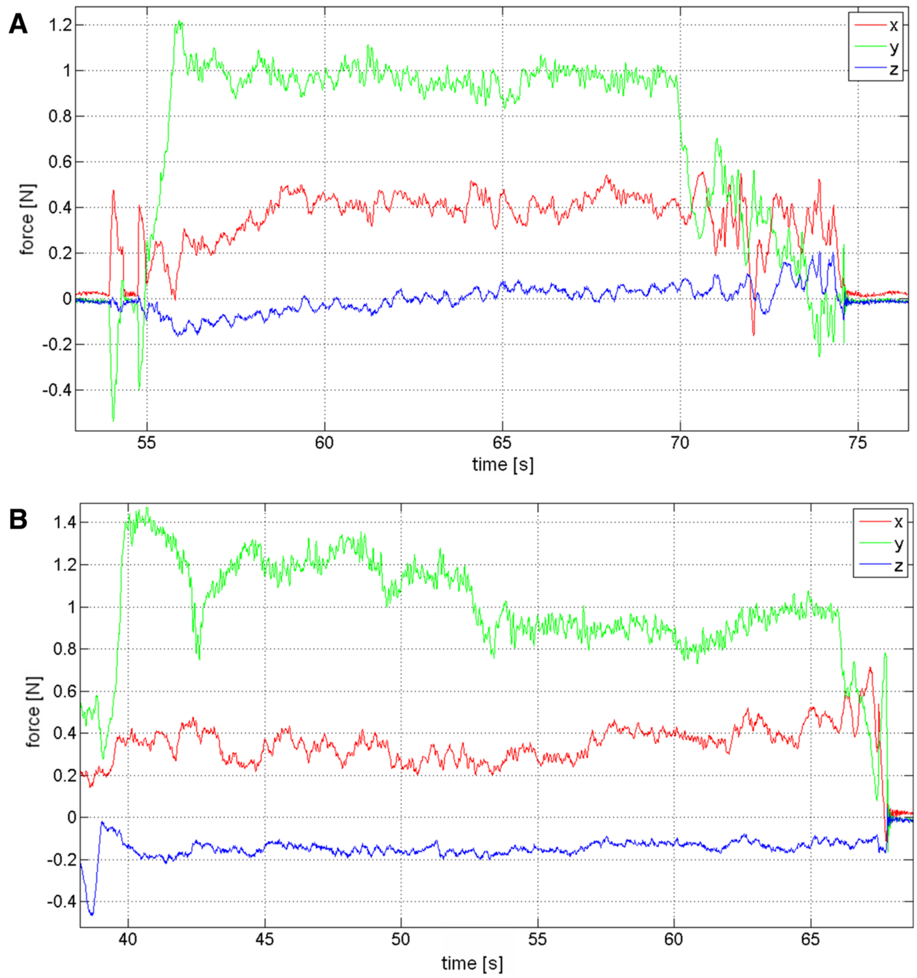

Fig. 4 **a** Time history of the spatial force components in test sequence S4 from an experienced surgeon. Note the stable force level in the axis of the instrument (*y*-axis, green line). **b** Time history of the spatial force components in test sequence S4 from a trainee with highly variable force levels in the axis of the instrument (*y*-axis, green line)

force amplitudes were registered in the S2 tasks when the test person had to push medially (Figs. 3, 5).

3. Applied forces were strongly dependent on the surgical experience of the test person. Notably, less experienced surgeons performed tasks with higher force levels than experienced surgeons.
4. During the static exercises S4 force amplitudes and force directions of trainees varied in a broader range compared to the experienced group (Figs. 4, 5).
5. Within one-directional manipulations S1 to S3, in most cases, the peak force amplitude of the repeated task was higher than in the first task. This could be seen in both the experienced and the less experienced group of surgeons (Fig. 3).
6. During complex manipulations such as crimping in task S5, experienced surgeons showed a stable repeatability of multiple crimp actions as can be observed in Fig. 6a, b. Trainees performed task S5 with very large variations and non-constant three-dimensional force patterns (Fig. 6c, d).

Discussion

Surgical precision at a microscopic scale is of crucial importance during otosurgery. It minimizes the risk of surgical damage of middle ear structures and has a significant influence on surgical outcome. Additionally, precise surgical manipulation helps to avoid the repetition of unsuccessful surgical steps, thus, it can shorten the time of surgery. Our study analyzed the surgical manipulations in otosurgery with the aim to define objective and quantifiable parameters describing surgical precision. Surgeons' tremor is definitely one factor that negatively influences surgical precision [1]. Tremor is usually considered as vibrational motions superposed to the desired motion of body elements. Here we distinguish between the phase of approaching the surgical instrument to the target object and the phase of interaction between surgical instrument and target object in the middle ear. During the first phase, tremor appears as vibrating deviations of the tool from the

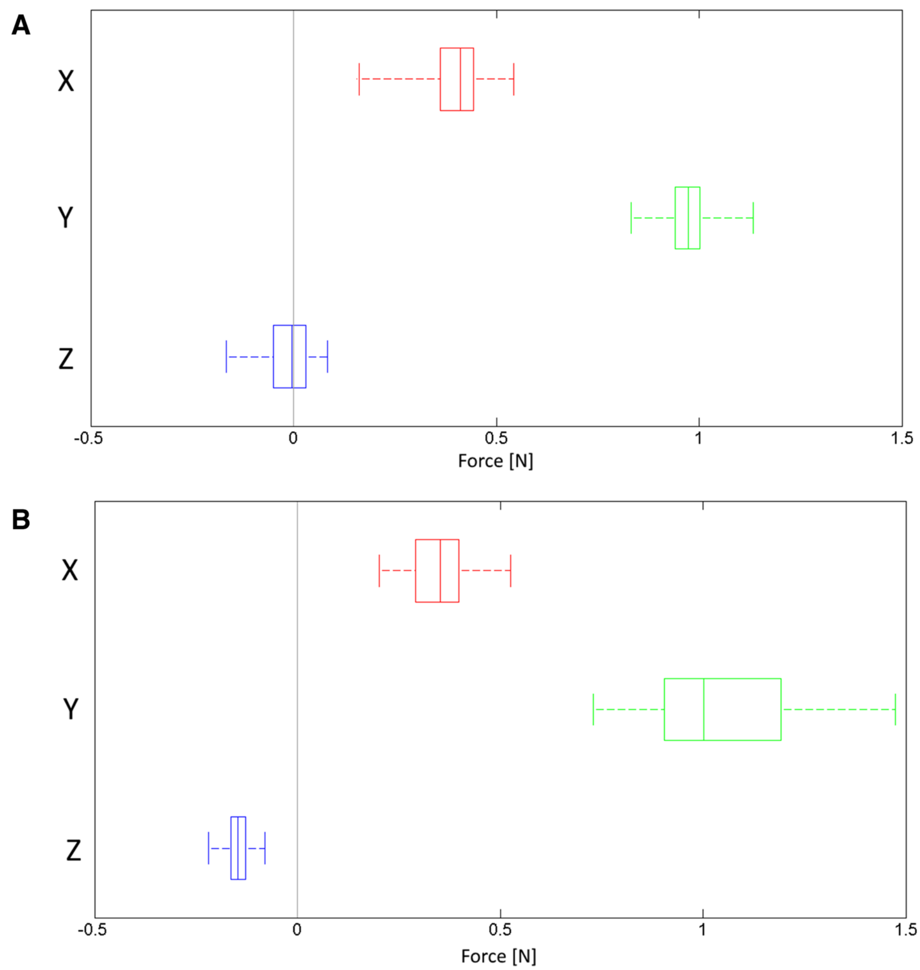

Fig. 5 **a, b** Force levels of all three spatial components from test sequence S4 presented in Fig. 4a, b, respectively. Note the highly variable force levels in test sequence S4 from the trainee (Fig. 4b) in the critical *y*-axis (axis of the instrument)

desired path and can be measured optically [1]. In the second phase when the tool is in contact with the ossicle, the tremor acts as a force excitation on the natural structures. Depending on the compliance and mass of the driven system, forces are transmitted to it. In our study, we measured and analyzed the transmitted forces in simulated otosurgical exercises on the long process of the incus in a model of the middle ear. The observed force fluctuations seem not to be intentional. They show mixed frequency patterns and some of them may be related to tremor.

Synopsis of key/new findings

The highest peaks of force were detected in the lateral–medial direction, i.e., along the axis of the otosurgical instrument (Figs. 3, 5). Our measurements have shown that even simple one-directional manipulation tasks result in three-dimensional force patterns (Fig. 3). Notably, this phenomenon can be demonstrated in both the trainees' and experienced surgeons' group. Three-dimensional force characteristics show inter- and intrapersonal variations. Force patterns are obviously different when comparing test groups of experienced surgeons and trainees. The measured forces from the latter group show higher peak values, higher fluctuations of force level (inconstancy), poorer repeatability of identical tasks and higher variations in the direction of the resulting force (unanisotropy) in comparison to the results from the experienced group of surgeons (Fig. 6a, d). The increase in peak force level in most of the second tasks of one-directional manipulations S1–S4 (Fig. 3) is probably due to haptic information on rigidity acquired by the first manipulation. By repeating the same task, the surgeon may rely more on visible control than on haptic feedback. However, experienced surgeons demonstrate their skills during repeated crimping by producing very similar force patterns with lower peak force amplitudes (Fig. 6a, d).

Strengths of the study

The set-up described has the specific feature that it combines video and 3-D force registration simultaneously. The system presented allows an objective assessment of manipulations at the long process of the incus based on measurements of all three spatial components of the force applied

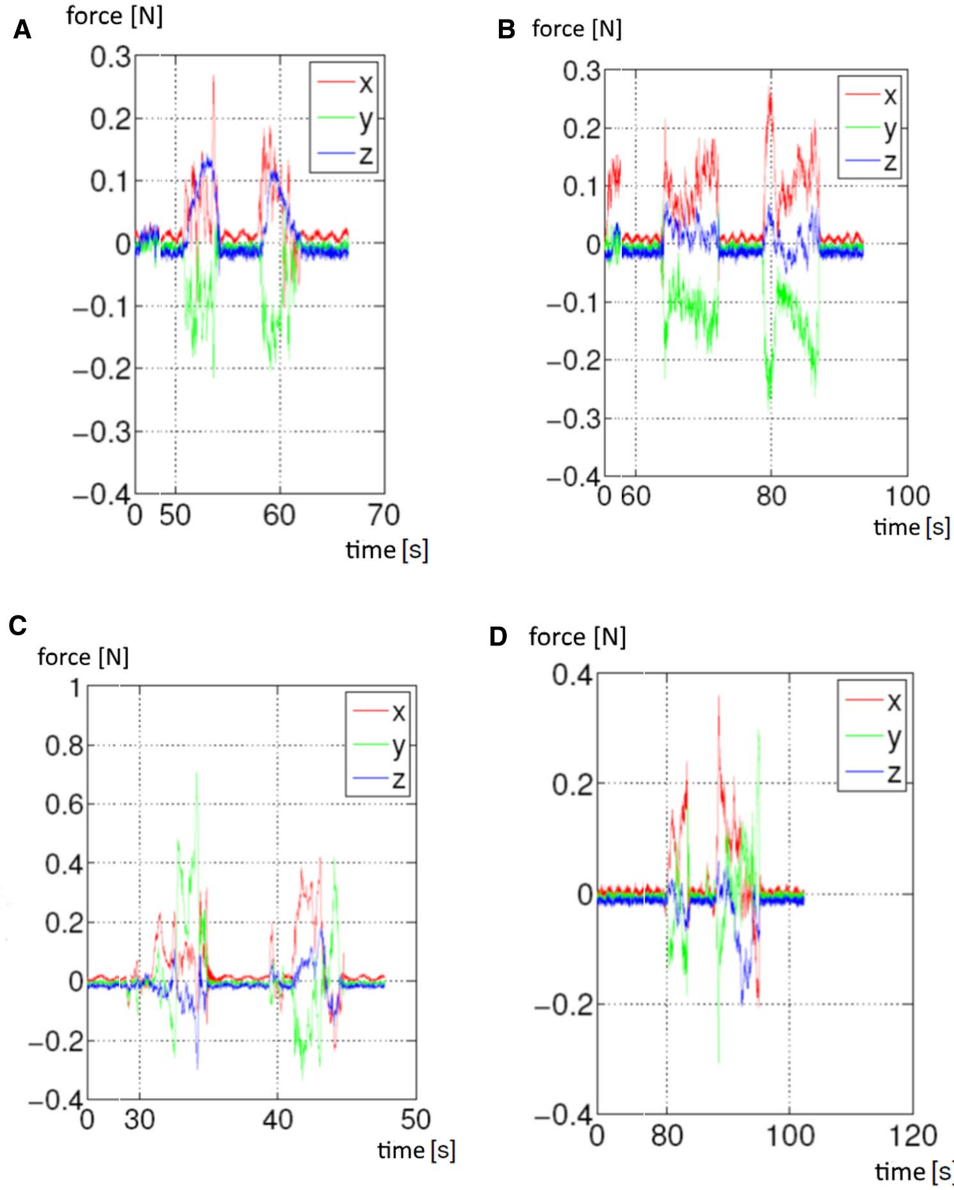

Fig. 6 a–d Simulation of crimping (fifth test sequence, S5). Examples for homogeneous force patterns with high reproducibility from two experienced otosurgeons (Fig. 6a, b). Inhomogeneous and less reproducible three-dimensional force patterns from two different trainees (Fig. 6c, d). Note the lower force amplitude of experienced otosurgeons versus trainees

by the surgeon. The measurements provided data about the temporal course of force characteristics during simulated otosurgical manipulations. This ongoing research identified objective assessment criteria for dexterity in simulated surgical manipulation, notably repeatability of identical tasks, and constancy of spatial force patterns and force magnitude. We also demonstrated several pitfalls in otosurgery related to the spatial orientation of the transmitted force, like the limited visual control in the axis of the surgical instruments as well as haptic control.

Comparison with other studies

A literature search reveals a few published laboratory training systems for ossiculoplasty [1–5]. Commercial training systems for otosurgery are mostly designed for the simulation of temporal bone drilling exercises. To date, several studies have been published dealing with force detection during middle ear surgery [6–13]. A recent paper provided data on force levels on the incus and stapes footplate during simulated prosthesis crimping [8]. Bergin et al. found three-dimensional force patterns in their study [6]. They used a specific tool during manipulation in temporal bones with a force microsensor coupled to the surgical instrument. A drawback of their system may be the cable of the force detector attached to the forceps, which potentially influences surgical manipulation and measurement results. In our system, no modification of the surgical instrument is necessary for testing. Compared to temporal bone experiments, measurements on our technical model are reproducible and comparable, as its properties are constant over time and there are no individual variations. On the other hand, the model incus has slightly different surface properties compared with natural ossicles in a living patient.

Clinical applicability of the study

In an earlier study by our workgroup, force values which could be tolerated by the incudomalleolar complex were described. In fresh temporal bone, micro-ruptures were detected in the lateral–medial force direction above 250 mN and the rupture force was defined to start at 570 (543–618) mN [10]. The presented measurements taken with our test rig reveal that trainees reach and ultrapass this critical force level in the axis of the instrument which means that there is a high risk of damaging the ligaments of the ossicular chain. In particular, repetitive ultrapassing of rupture force level during a task will potentially increase the number of ruptured fibers in a ligament. Thus, a swift and systematic operation procedure seems to have a lower risk of damaging than longlasting attempts. Less experienced otosurgeons should be aware of the different patterns of applied force on middle ear structures during surgical manipulation so as to reduce the risk of damage to ossicle ligaments or incus luxation. The control of surgical manipulation is mainly visual but also haptic [7]. Tactile feedback is very important in otosurgery. One issue is checking chain motility to detect fixation of the malleus head or the stapes footplate [7, 11–13]. Other issues are prosthesis crimping in stapes surgery or removal of epithelium from the ossicular chain in cholesteatoma surgery. Experienced surgeons rely more on haptic feedback during otosurgery than trainees do [7]. Due to the restricted view in the axis of the instrument, the force component is of great importance. Obviously, trainees had the highest force amplitudes in this *y*-axis (Figs. 4a, b, 5a, b). Furthermore, our data demonstrate that less experienced surgeons have non-constant force amplitudes during static exercises (Figs. 4a, b, 5a, b). Besides the lack of specific training in haptic feedback, this phenomenon may also be due to the dominantly visual control of surgical manipulation by trainees.

The test rig presented here is a useful device providing feedback on surgical techniques and skill developments, especially for trainees. It can be used for simulation of specific surgical steps in the middle ear, e.g., prosthesis crimping in stapes surgery or attachment of the floating mass transducer to the ossicular chain in active middle ear implants [14, 15]. Trainees obtain feedback on their otosurgical manipulations qualitatively in terms of time history and video records as well as quantitatively in terms of force levels. They can individually find and define an appropriate procedure for specific difficult tasks. The training of otosurgical steps in a laboratory environment with video and force feedback may shorten the learning curve and help trainees to avoid injury to the ossicular chain during surgery in patients. Therefore, the integration of laboratory learning, training and testing is recommended in surgical education.

Acknowledgements We acknowledge Prof. Robert Mlynski, director of the Department of Otorhinolaryngology, Head and Neck Surgery "Otto Koerner", Rostock University Medical Center, Rostock, Germany for his help in critical reviewing of the manuscript.

Compliance with ethical standards

Ethical standards All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants included in the study.

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