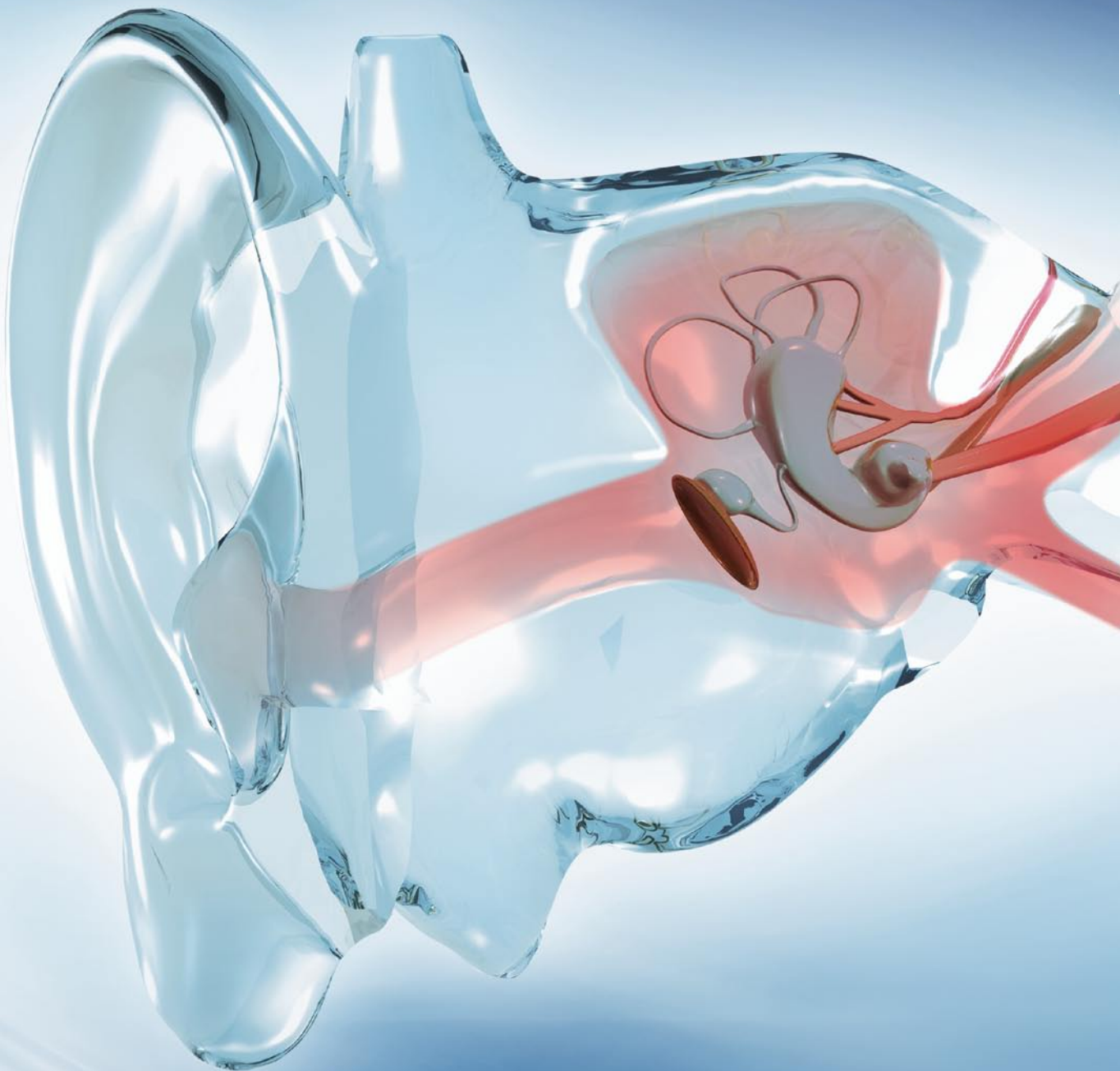


All Ears

Biomechanics: Research on the middle ear helps develop new hearing aids



The ability to communicate is an elementary part of our lives. And without good hearing, communication becomes difficult if not impossible. This is why researchers continue to work on optimizing prostheses that improve hearing. Now researchers at the Universität Stuttgart in Germany have opened up a new avenue of exploration for developing middle ear prostheses. Their investigations concentrated on the impact of the ossicular chain in the middle ear, which directly affects hearing.



How We Hear

The hearing organ must convert air pressure fluctuations into neural impulses to make them accessible to the brain. It does so via a complex chain of elements with overlapping functions. Simply put: Sound waves enter the auditory canal as air pressure fluctuations and put the auditory ossicles (the hammer, also known as the malleus, the anvil or incus, and the stirrup or stapes) in the middle ear in motion. The footplate of the stapes rests on the inner ear. Behind it lies the inner ear fluid, which fills the vestibular system and the cochlea. The movements of the stapes footplate put the inner ear fluid into motion, which excites the sensory hair cells. The deformation of these cells creates electric signals, which are sent to the brain via the auditory nerve and cause the actual perception of sound.

The Impact of Rocking Motions on Hearing

To improve the prosthesis, the research team at the Universität Stuttgart wants to ascertain how the ossicular chain must be stimulated for humans to hear as well as possible.

The stapes performs both piston-like and rocking motions, depending on the frequency.

- At low frequencies, there is mainly piston-like motion.
- At high frequencies, additional rocking motions also occur.

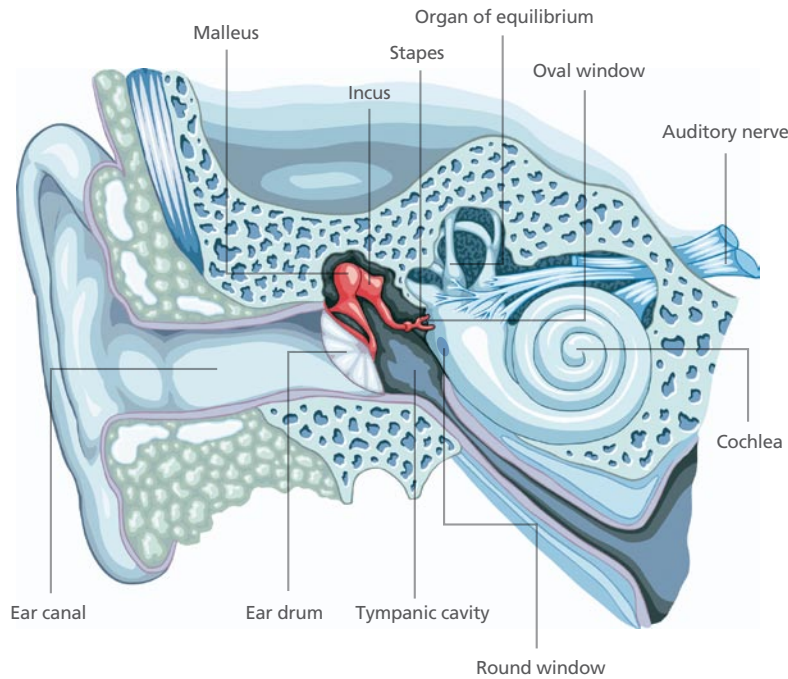
Researching the Impact of Rocking Motions

The classic theory on hearing states that only the piston-like motions of the stapes footplate directly influence hearing, not the rocking motions. The goal of the research team at the Universität Stuttgart and at University Hospital Zürich in Switzerland is to discover whether, and to what extent, the rocking motions excite the hair cells and trigger signals to the brain to produce auditory perception. In-vivo experiments were therefore performed on guinea pigs.

Test Setup with Modern Microsystem Technology

The test setup consists of:

- An anesthetic and monitoring device for the experimentee
- A vibration-damped test rig in a booth isolated from acoustic background noise and electromagnetic radiation
- An apparatus to mechanically excite the stapes with a piezoelectric actuator
- Data acquisition of the stapes motions and the nerve potential



The anatomy of human hearing.

Mechanical Stimulation of Hearing

In comparison to acoustic excitation via a loudspeaker, mechanical excitation at the head of the isolated stapes makes it possible to specify the form of the footplate's motion. The actuator with its three independent piezoactuators can then carry out any kind of complex spatial motion. In particular, piston-like stapes motions can be generated, as well as pure rocking motions. In comparison, with acoustic excitation, the relationship between the rocking and piston-like motions of the

“Insufficient measurement methods were the reason why it was assumed that the rocking motions of the stapes footplate do not cause an auditory event. State-of-the-art microsystem technology at long last lets us superimpose rocking motions onto the hearing organ in a high-frequency range and measure them.”

Dr. Ing. Albrecht Eiber, Institute of Engineering and Computational Mechanics, Universität Stuttgart, Germany

“Insufficient measurement methods were the reason why it was assumed that rocking motions of the stapes footplate do not result in nerve stimulation,” explains Dr. Albrecht Eiber from the Institute of Engineering and Computational Mechanics at the Universität Stuttgart. “State-of-the-art microsystem technology has at long last enabled us to measure the rocking motions and their impact in the high-frequency range.”

When investigating the vibrations of the auditory ossicles in the nanometer range, it is common to use laser Doppler vibrometers. In this experiment, a 3-D laser captures the speeds of the stapes head simultaneously in all spatial directions and amplifies the electric voltage of the

electrophysiological response by the experimentee's auditory nerve via a very high-ohm biosignal amplifier.

Surgical Intervention in the Middle Ear

The stapes of the guinea pig is laid open surgically while maintaining the inner ear function. The actuator and the laser beams thus have direct access to the head of the stapes. A specially designed needle and the finest ophthalmic surgical threads couple the piezoelectric actuator to the head of the stapes. These meticulous surgical tasks and the monitoring of the experimentee's anesthetic status were performed by PD Dr. med. Alexander Huber from the Universitätsspital Zürich.

stapes is a fixed, frequency-dependent relationship, determined by the dynamics of the chain. A motion corresponding to acoustic excitation can also be superimposed at the head of the stapes. This makes it possible to compare the measured nerve potentials with the results from other research groups.

Drive Concept of the Actuator

The time progression of the stapes motion determines the frequency content of the signal, and thus also the excitation of the inner and outer hair cells at the frequency-specific location of the basilar membrane. The acoustic click stimulus commonly used in electrocochleography has a wide frequency spectrum. The dynamics of the vibrating system for

“The DS1005 PPC Board drives the actuator. With the three independent piezo actuators, the elementary piston-like and rocking motions of the stapes can be defined precisely and excited highly dynamically.”

Dr. Ing. Michael Lauxmann, Institute of Engineering and Computational Mechanics, Universität Stuttgart, Germany

acoustic excitation, consisting of a loudspeaker, transmission tube, ear channel and middle ear, mean that stimulus behavior over time in the inner ear is noticeably low-pass filtered. A short, high-frequency click on the sonic converter has an extremely limited bandwidth and experiences a delay due to the signal execution time. This makes it possible to reproduce an acoustic click by direct stimulus at the head of the stapes using a slower mechanical drive system.

The modular hardware by dSPACE optimally generates the stimulus forms necessary for the experiment. “The dSPACE DS1005 PPC Board is used to drive the actuator,” explains Dipl.-Ing. Michael Lauxmann from the Institute of Engineering and Computational Mechanics at the Universität Stuttgart. “With reference to the dynamics of the ossicular chain and the actuator, we calculate beforehand how we need to operate the actuator in order to achieve the desired stimulus for the head of the stapes. We use a multi-sinus signal to identify the system dynamics.”

Recording the Nerve Potentials

Measurement is performed via an amplifier with a high-ohm input and a high amplification factor. However, the signal of the stimulus response contains a high level of disturbance resulting from the experimental environment and the basic activity of the nerves. For this reason, a

number of stimulus responses are recorded and the uncorrelated disturbances are reduced by averaging. To do so, clicks are output at intervals of 50 ms, for example. To obtain consistent measurement data, the physical condition of the experimentee and the positions of the electrodes need to be monitored, as in a real surgical operation, and should remain as constant as possible.

Impact of the Stapes Footplate's Rocking Motions

By imprinting both the elementary piston-like and rocking motions, the nerve potentials known from elec-

trochleography were verified. The experiments showed for the first time that in contrast to what was previously thought, rocking motions do in fact trigger nerve stimuli. The form and latencies of the sensory cells' responses to rocking motions, depending on the intensity of the stimulus, correspond to the neural responses previously only observed in the case of piston motions.

Stimulus and Data Recording with the dSPACE AutoBox

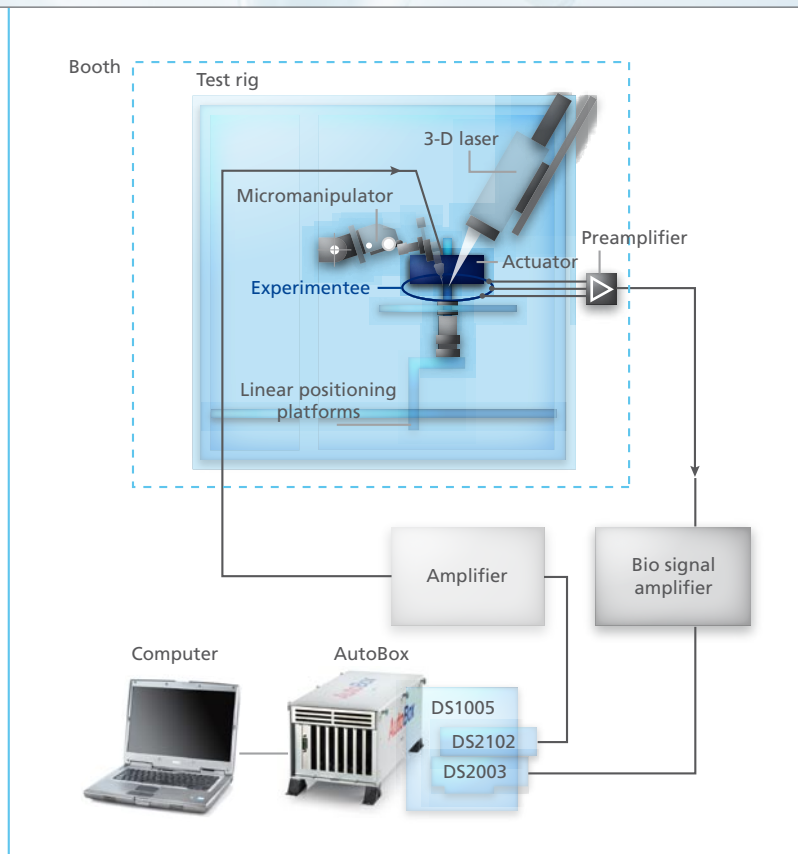
The dSPACE AutoBox is used to operate the test rig and record the data. “Following good experience

Dr. Ing. Albrecht Eiber (right) and Dipl. Ing. Michael Lauxmann (left), Institute of Engineering and Computational Mechanics, Universität Stuttgart, Germany.



with dSPACE when running test benches in mechatronics, we decided to choose dSPACE for our biomechanical experiments as well,” reports the commissioned researcher, Dr. Albrecht Eiber. One part of the system is the DS1005 PPC Board, where the measurement program runs in real time. Additional modular hardware components from dSPACE, like the DS2102 High-Resolution D/A Board, perform the analog output of the measurement program values, and the DS2003 Multi-Channel A/D Board reads in the input of analog signals.

The modular setup of the dSPACE system and its high flexibility allow



Components and signal flow of the experiment setup.

“Following good experience with dSPACE when running test benches in mechatronics, we decided to choose dSPACE for our biomechanical experiments as well.”

Dr. Ing. Albrecht Eiber, Institute of Engineering and Computational Mechanics, Universität Stuttgart

measurement cycles to a minimum, since there are fewer manual steps and because it is not necessary to document the experiment setup parameters manually. The automated test sequence is as follows:

- Input of the stimulus via ControlDesk
- Starting the measurement procedure via MATLAB command lines
- Saving the measurement data and controlling the measurement via MATLAB

Positive Measurement Results and the Need for Further Research

The collected data challenges the theory that only piston-like stapes motion causes the sense of hearing, not rocking motion. The results show that all complex stapes footplate motions, piston motion and rocking, activate the inner ear and thus cause an auditory event. For statistical evaluation of the experiments, further experimentees must be studied.

If further experiments prove that

us to match the measurement environment quickly and optimally to any kind of inquiries in the field of biomechanics,” continues researcher Dr. Eiber. The dSPACE experiment software ControlDesk controls the measurement program on the real-time processor. The execution of the experiment is automated and accelerated by MATLAB 2008a. In addition, dSPACE provides a library of MLib functions for data transfer between the memory of the measurement processor and the RAM from MATLAB.

After the experiment is carried out, the data is transferred to MATLAB. This keeps time between the two

Glossary

Basilar membrane –

Membrane in the cochlea whose movements are converted into nerve impulses via the hair cells. The impulses are carried to the brain by the auditory nerve, where they generate the actual perception of sound.

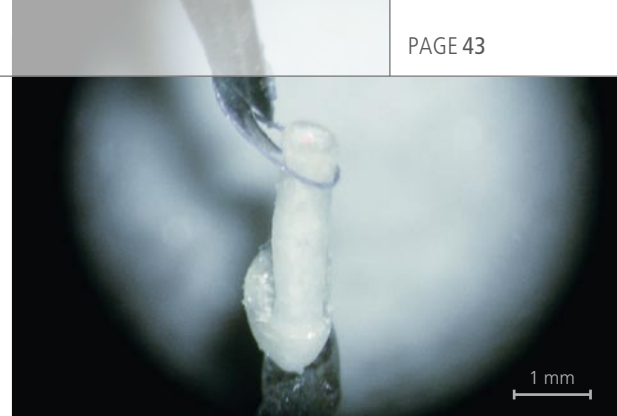
Electrocochleography –

Examination method used in ear, nose and throat medicine to measure the potentials generated in response to acoustic stimuli inside the cochlea.

Short and long axes –

The stapes has two characteristic stirrups that start at the footplate and meet at the head of the bone. The footplate is oval in shape, so it has one short and one long axle.

A thread is used to connect the actuator needle and stapes.



rocking motions of the stapes also set off a hearing stimulus, this will have a long-term impact on the goals for the improvement of middle ear prostheses. If so, any implant can no longer be evaluated solely

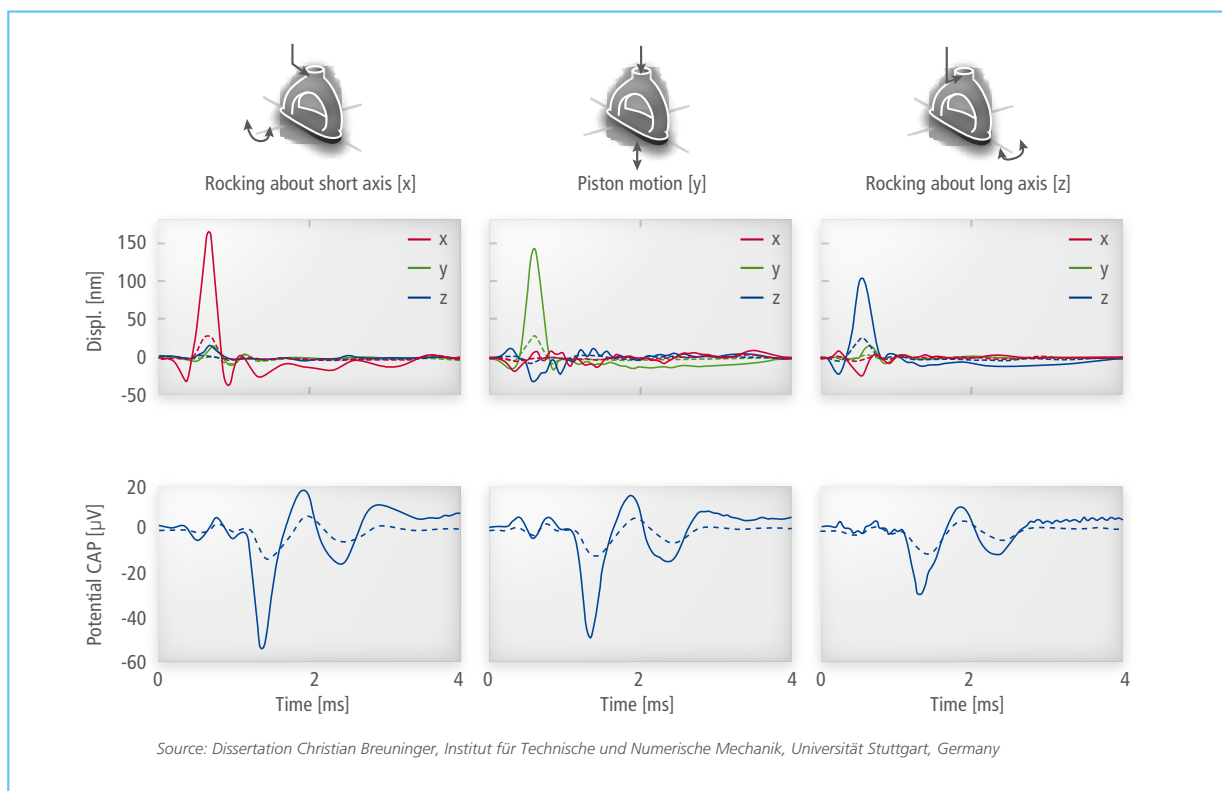
on the basis of the piston-like stapes that it generates. The complex spatial motion of the stapes would be the new criterion for evaluating an implant's performance. ■

“The modular setup of the dSPACE system and its high flexibility allow us to match the measurement environment quickly and optimally to any kind of issues in the field of biomechanics.”

Dr. Ing. Albrecht Eiber, Institute of Engineering and Computational Mechanics, Universität Stuttgart

Summary

- A research team at the Universität Stuttgart contributes vital knowledge for developing newer middle ear prostheses that improve hearing.
- The experiments investigate whether the rocking motions of the stapes cause a hearing stimulus in the middle ear.
- dSPACE products help answer complex questions in the field of biomechanics.
- The modular setup and flexible use of the dSPACE equipment provided ideal conditions for performing research.



Compound action potential (CAP) for piston-like and rocking motions of the stapes footplate. The continuous line shows a strong stimulus, the dashed line shows a weaker stimulus.