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Biomechanics of the incudo-malleolar-joint — Experimental investigations for quasi-static loads

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ABSTRACT

Under large quasi-static loads, the incudo-malleolar joint (IMJ), connecting the malleus and the incus, is highly mobile. It can be classified as a mechanical filter decoupling large quasi-static motions while transferring small dynamic excitations. This is presumed to be due to the complex geometry of the joint inducing a spatial decoupling between the malleus and incus under large quasi-static loads.

Spatial Laser Doppler Vibrometer (LDV) displacement measurements on isolated malleus-incus-complexes (MICs) were performed. With the malleus firmly attached to a probe holder, the incus was excited by applying quasi-static forces at different points. For each force application point the resulting displacement was measured subsequently at different points on the incus. The location of the force application point and the LDV measurement points were calculated in a post-processing step combining the position of the LDV points with geometric data of the MIC. The rigid body motion of the incus was then calculated from the multiple displacement measurements for each force application point. The contact regions of the articular surfaces for different load configurations were calculated by applying the reconstructed motion to the geometry model of the MIC and calculate the minimal distance of the articular surfaces.

The reconstructed motion has a complex spatial characteristic and varies for different force application points. The motion changed with increasing load caused by the kinematic guidance of the articular surfaces of the joint. The IMJ permits a relative large rotation around the anterior-posterior axis through the joint when a force is applied at the lenticularis in lateral direction before impeding the motion. This is part of the decoupling of the malleus motion from the incus motion in case of large quasi-static loads.

1. Introduction

Beside the small acoustically induced vibrations, the human middle ear has to handle large quasi-static pressure variations. Those pressure variations are several orders of magnitude larger than the acoustically induced pressure levels and are caused by ambient pressure changes as well as by every day activities like taking an elevator, flying or even changing the body posture, e.g. Hüttenbrink (1997); Dirckx (2007); Mirza and Richardson (2005).

This raises the question, how can the middle ear tolerate those massive static pressure variations while maintaining its function in case of the sound transfer? Hüttenbrink (1988) investigated the motion of the ossicular chain while applying large quasi-static pressures (± 4 kPa) to the tympanic membrane. He describes flexibility within the middle ear joints protecting the inner ear by decoupling the motion of the malleus from the ossicular chain. He proposed that the complex geometric structure of the Incudo-Malleolar-Joint (IMJ) induces a change of the motion of the incus decoupling it from the stapes. Other studies have also reported a relative motion within the IMJ in case of quasi-static loads, e.g. Cancura (1980); Schön and Müller (1999).

The IMJ is known to be a true diarthrodial joint with a complex saddle shaped form of the articular faces, as described in Marquet (1981); Kirikae (1960); Etholm and Belal Jr. (1974); Harty (1964); Sim and Puria (2007). Both the complex shape of the articular surface of the joint and the described spatial motion of the ossicles indicate the need of three dimensional measurements of the relative joint motion for understanding the biomechanics of the IMJ. Three dimensional investigations of the dynamic vibration of the complete ossicular chain of the middle ear with LDVs considering

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the geometric structure of the ossicles have been performed in the past, e.g. Decraemer et al. (1994, 2014). To our knowledge the spatial motion of the malleus incus complex (MIC) in case of quasi-static excitation has not been investigated by spatial LDV displacement yet. Therefore we created a measurement setup capable of capturing the spatial displacement within the IMJ and correlate this motion with the geometry of the joint surface, see Ihrle et al. (2015).

The goal of this study was to investigate the mechanical behavior of the IMJ in case of quasi-static loads. To exclude the effects of other middle ear components we performed measurements on isolated MICs. We measured the spatial motion of the MIC with a 3D-LDV and reconstructed the rigid body motion. In combination with the geometry of the MIC obtained from micro-CT scans the motion was correlated with the structure of the articular surfaces of the joint.

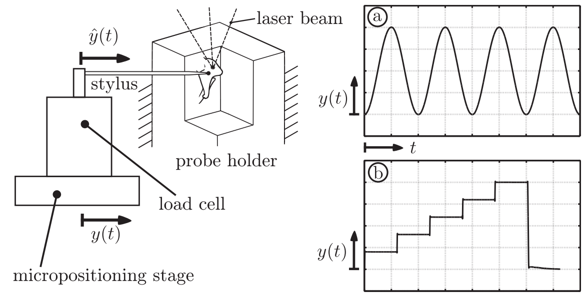

Fig. 2. Schematic depiction of the excitation of the incus by a stylus. The stylus is connected to a load cell and driven by an electronic micro-positioning stage. Two kinds of excitation were used: a low frequency sinusoidal and an incremental step displacements signal. The spatial displacement of several points on the incus surface was measured by a combination of three 1D-LDVs.

2. Material and methods

2.1. Temporal bone preparation

Measurements were performed on five isolated MIC harvested from fresh human temporal bones (TBs) (41–70 years old). The temporal bones were harvested within 24 h after death and preserved in 0.1% thiomersal solution at 4° C. The MIC was extracted by removing the tympanic membrane, the ligaments and the tensor tympani from the TB, and cutting the incudo-stapedial joint. The isolated MICs were checked under a microscope for damage of the joint. One MIC was excluded during the first step of measurement resulting in 4 TBs for the analysis presented in this paper.

The malleus was fixed to a probe holder with hystoacryl glue. The malleus was orientated with the axis from the umbo to the superior top of the malleus head aligned parallel to the vertical edges of the probe holder. The IMJ and the incus were able to move free and visual access was facilitated by the form of the probe holder. Foam material was placed on the block and flushed with saline solution to keep the sample moist during the measurements. Additionally, drops of saline solution were applied with a syringe to the MICs in-between the different measurements steps. Fig. 1 shows the orientation of the four MICs attached to the probe holder.

2.2. Measurement system

The measurement setup and procedure are described briefly as they have been previously described in work (Ihrle et al. (2015)) related to equivalent experiments performed on artificial ossicles as a prior step to investigations on human TBs. This previous works includes descriptions of details about the measurement setup and procedure as well as the performance of the developed data- and post-processing methods has been described in detail in this previous work.

Generally, spatial Laser Doppler Vibrometer (LDV) displacement measurements were performed subsequently at several points on the incus surface with the excitation retained unchanged. The incus was excited by a stylus, while measuring the applied force and the displacement of the stylus, as shown in Fig. 2. By combining the LDV measurements from multiple points, the rigid body motion of the incus was calculated. The following procedure was repeated for each force application point: (1) A time–displacement profile of the micropositioning stage is defined; (2) The spatial displacement at different laser measurement points on the specimen surface is measured, while retaining both the time–displacement profile and the force application point unchanged. Before starting the measurement the specimen was preconditioned by applying a sinusoidal displacement profile.

2.2.1. Excitation of the malleus incus complex

In the experiments two kinds of signals were used: a low-frequency sinusoidal excitation (0.05–0.1 Hz) and a step displacement profile, both shown in Fig. 2. The sinusoidal yields the nonlinear quasi-static stiffness-values and the spatial motion of the

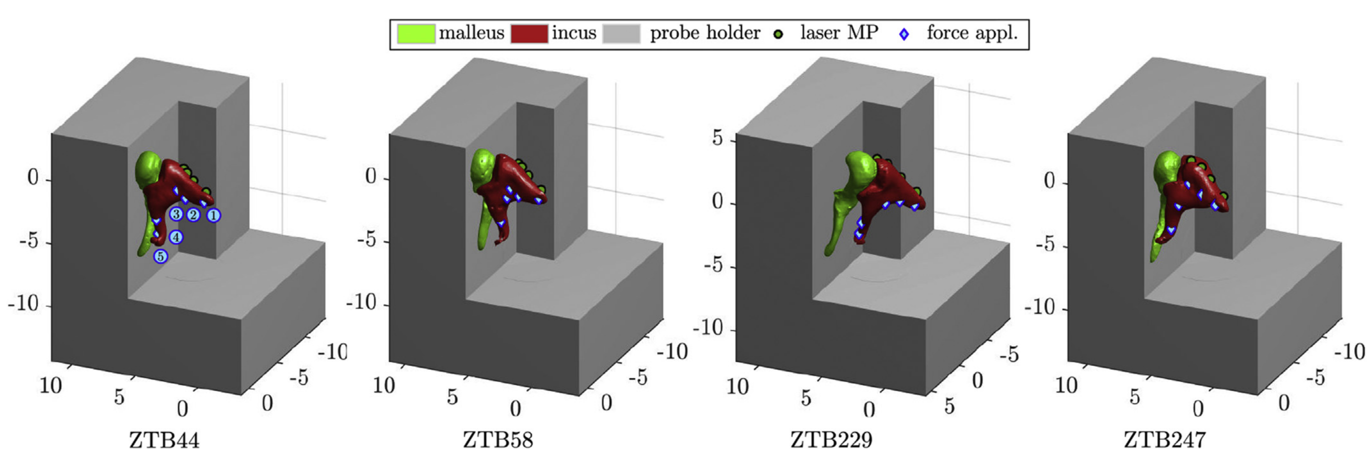

Fig. 1. Orientation of the isolated malleus incus complexes (MICs) attached to the probe holder. The force application points are highlighted in blue with the numbering being consistent for all TBs. The laser measurement point are located at the superior-lateral side of the short process of incus and highlighted in green. The geometry is obtained from micro-CT scans after the measurements while the was MIC still connected to the probe holder.

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