Three-dimensional quasi-static displacement of human middle-ear ossicles under static pressure loads: Measurement using a stereo camera system

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Abstract

The time delay and/or malfunctioning of the Eustachian tube may cause pressure differences across the tympanic membrane, resulting in quasi-static movements of the middle-ear ossicles. While quasi-static displacements of the human middle-ear ossicles have been measured one- or two-dimensionally in previous studies, this study presents an approach to trace three-dimensional movements of the human middle-ear ossicles under static pressure loads in the ear canal (EC). The three-dimensional quasi-static movements of the middle-ear ossicles were measured using a custom-made stereo camera system. Two cameras were assembled with a relative angle of 7° and then mounted onto a robot arm. Red fluorescent beads of a 106–125 μm diameter were placed on the middle-ear ossicles, and quasi-static position changes of the fluorescent beads under static pressure loads were traced by the stereo camera system. All the position changes of the ossicles were registered to the anatomical intrinsic frame based on the stapes footplate, which was obtained from μ-CT imaging. Under negative ear-canal pressures, a rotational movement around the anterior-posterior axis was dominant for the malleus-incus complex, with small relative movements between the two ossicles. The stapes showed translation toward the lateral direction and rotation around the long axis of the stapes footplate. Under positive EC pressures, relative motion between the malleus and the incus at the IM became larger, reducing movements of the incus and stapes considerably and thus performing a protection function for the inner-ear structures. Three-dimensional tracing of the middle-ear ossicular chain provides a better understanding of the protection function of the human middle ear under static pressure loads as immediate responses without time delay.

Keywords:
Ambient pressure variation
Micro-computed tomography imaging
Middle-ear ossicles
Protection function
Quasi-static displacement
Static pressure
Static pressure loads
Stereo camera system
Three-dimensional displacement

1. Introduction

The human middle-ear cavity (also called the tympanic cavity), surrounded by the tympanic part of the temporal bone, is a pressure-sealed space. The static pressure in the human middle-ear cavity is actively and passively regulated under surrounding static pressure variation by the opening of the Eustachian tube. However, the function of this ventilation system is time-delayed and can malfunction under specific conditions, e.g., in the case of otitis media. Therefore, static pressure differences between the ear canal (EC) and the middle-ear cavity may occur in our daily life. During static pressure differences between the cavity and its surroundings, sounds are perceived altered, muffled and dull, especially at lower frequencies. Already in 1864, Politzer observed that the acoustically induced ossicular vibrations are attenuated under static pressure changes in the middle ear cavity depending on the amount of pressure applied (Politzer, 1864). Later studies (e.g., Murakami et al., 1997; Gan et al., 2006; Homma et al., 2010; Warnholtz et al., 2021) showed from their measurements using laser Doppler vibrometry that such static pressure difference across the tympanic membrane attenuates middle-ear sound transmission through the human middle ear at low frequencies below the first resonance of the middle-ear ossicular chain.

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Wanholtz et al. (2021) demonstrated from their experimental work that the flexibility of the incudo-malleal joint (IMJ) in the human middle ear reduced the attenuation of the middle-ear sound transmission, thereby performing a kind of adaptation function to sudden changes of ambient static pressure before opening of the Eustachian tube or under pressure-equalization malfunctions.

In addition to the influence of the static pressure loads on middle-ear sound transmission, which is related to the vibrational motion of the middle-ear ossicular chain, quasi-static behavior of the middle-ear ossicular chain under static pressure loads has been investigated. For example, already in 1880, inward and outward movements of the middle-ear ossicles under pressure variations using a labyrinth manometer were examined by Bezold. He noticed that the outward movement of the ossicular chain was twice as large as the inward movement. He further described that with increasing pressure, additional pressure-induced movement of the ossicular complex became smaller, being saturated when the maximum was reached (Bezold, 1880). One hundred years later, more detailed measurements on the ossicular displacements under static pressure changes were performed by Hüttenbrink (1987, 1988, 1997), using a microscopic approach. He investigated static displacements of the umbo, lenticular process, and stapes head under static pressure loads, and observed reduced inward and outward movements (especially inward movements) of the lenticular process and stapes compared to the corresponding movements of the umbo. According to his studies, such a reduction in quasi-static displacements through the middle-ear sound transmission line is mainly due to absorption of the large movement of the malleus at the flexible IMJ of the human middle ear. Supporting Hüttenbrink's work, Ihle et al. (2016) showed that the two articular faces at the IMJ start to glide with static loads above a certain amount, generating relative displacements between the malleus and the incus. The works by the two groups proposed that this reduction of quasi-static displacements at the IMJ provides a protection function for inner-ear structures against sudden change of surrounding static pressure, as an immediate response before pressure equalization by opening of the Eustachian tube or under Eustachian tube dysfunction.

While previous measurements of the static behavior of the middle-ear ossicular chain have been done in one-dimensional (1D) or two-dimensional (2D) ways, the present study introduces a custom-made stereo camera system to measure three-dimensional (3D) movements of the ossicles. Though stereo camera systems have been widely used to measure displacements as well as distances in many fields, the stereo camera approach in the middle ear has been limited to measurements of distance and 3D location. For example, Gao et al. (2013) used stereo vision and based thereon 3D reconstruction of the middle ear in order to identify precise drug allocation to the round window. In the present study, a custom-made stereo camera system is used to track rigid-body movements of the human middle-ear ossicles under static pressure loads. In addition, in combination with micro-computed tomography (µ-CT) imaging, rigid-body movements of the ossicles are registered to the anatomical frame for comparison across the samples (Sim et al., 2012).

2. Methodology

This study was executed under the ethical approval of the Swiss Ethic Commission of Canton Zürich with the identification number KEK-ZH-Nr. 2014-0544.

2.1. Stereo camera system and calibration

A stereo camera system, comprised of two 8MP USB cameras (#ELP-USB8MP02G-MFV, Ailipu Technology Co. Ltd., China) with magnification optics (1x magnification, numerical aperture = 0.03, tube length = 160, Leefun, China) and a 35 mm extension tube, was set up. The resultant field of view was approximately 4.6 × 6.1 mm on the object plane, with a spatial resolution of <2 µm per pixel. The two cameras were assembled with a relative angle of 7° and a working distance (from the tip of the optics to the object plane) of approximately 15 cm, thereby allowing for optical access of both cameras to the middle-ear ossicles. Further, the stereo camera system was mounted onto a robot arm for precise control of its position and orientation relative to the sample.

A Matlab (Mathworks) script was implemented, which allowed for rapid (within 1 ms per camera) capture of pictures from both cameras, sequentially. The camera system was calibrated, using a ceramic checkerboard-patterned target with a grid size of 250 × 250 µm and a feature-to-feature accuracy of 1 µm (#WMT-032-0.25-C, Dot-vision, China). The target was mounted onto a gimbal stage and at least two pictures from different angles covering different areas of the overlapping view were taken with each camera. Using the camera calibration toolbox in Matlab, distortions of the imaging pathway were calibrated based on a pinhole camera model with the addition of a lens distortion model (Heikkila et al., 1997; Zhang, 2000). The procedure was customized to allow for a reliable calibration by detecting all corners of a calibration target with higher density (500 corners versus 10-20 in the standard procedure) in each calibration image. This allowed for use of fewer calibration images than the standard procedure (i.e., only 1 versus 5–10). The calibration process obtains the intrinsic and extrinsic parameters of both cameras, including lens distortion parameters (intrinsuc) and the geometric relationship of the two cameras (extrinsic), expressed as rotation and translation matrices. World points, i.e., the real-world coordinates, are transformed into the camera coordinate system using the extrinsic parameters, while the intrinsic parameters are used for mapping the camera coordinates into the image plane.

As a means of accuracy, the reprojection error was used, which is the distance between the pattern corners detected in the calibration images and the corresponding world points of those pattern corners projected into the same image. A mean reprojection error of less than half a pixel was achieved for all calibrations. The system was further tested by moving fluorescent beads (later used as targets, diameter: 106–125 µm, fluorescent red under 300–550 nm wavelengths, #UVFMS-BR-1.090-106-125um, Co- pheric LLC, USA) in 10 and 100 µm increments using micrometre stages (accuracy stages ~10 µm). All movements could be tracked with an accuracy of ~10 µm, i.e., the maximum accuracy achievable due to the limitations of the stages, independent of directionality within ±5 mm of the focal depth, which represents the focal depth range needed for tracking the middle-ear structures.

2.2. Temporal bone preparation and static pressure regulation

Frozen human cadaveric temporal bones (TBs) obtained from Science Care (Phoenix, Arizona, USA) or RISE Labs (Amsterdam, Netherlands) were used in this study. To confirm normal behavior of the TBs, vibrations of the stapes footplate center in response to acoustic stimuli were measured and only temporal bones within the American Society for Testing and Materials (ASTM) F2504-05 standard (2005) were further used in the study. Consequently, five human TBs (3 from Science Care and 2 from RISE Labs) were included in this study.

The TBs were harvested between 48 and 72 h after death and were kept frozen at ~20 °C until preparation for measurements. A wide mastoidectomy was performed to allow a large access to the middle-ear ossicles, and in addition, the tectum surrounding the IMJ was drilled away. The middle-ear suspensory attachments as well as the inner ear were kept intact. The facial nerve was care-
fully removed to obtain better access to the stapes. Six-to-seven reference marker wires were placed in the periphery of the middle ear, to correlate the coordinate system of the stereo camera system with the intrinsic anatomical frame obtained from μCT-imaging. These reference marker wires were further used to verify that the sample did not move throughout the experiment.

The EC was drilled down and replaced by a plastic artificial ear canal (AEC). The AEC was glued to the bony rim of the tympanic membrane using an epoxy glue (Rapid, Araldite) to achieve a stable and tight pressure seal. Static pressures in the range of ±3 kPa were generated by a pressure regulator PQ1 (AirCom Pneumatic GmbH, Germany), and the static pressure in the AEC was monitored using an electronic pressure gauge HCLA0075B (First Sensor AG, Germany), and was controlled within ±50 Pa of the targeted static pressure. The methods to generate and control static pressures in the AEC were the same as the methods used for our previous study (Warnholz et al., 2021).

2.3. Measurement of quasi-static displacements of middle-ear ossicles

Red fluorescent beads of 106- to 125-μm diameter (see Section 2.1) were placed on the middle-ear structures for tracking (see Fig. 1). The bone was illuminated by a blue light (white light source filtered by a dichroic filter (#FD18, Thorlabs, USA; >85% average transmission for 390–480 nm)), to increase visibility of the fluorescent beads.

The middle-ear ossicles were accessed by both cameras from three different angles (1–3) by changing the position of the stereo camera system: (1) access to the stapes through the wide mastoidectomy (Fig. 1), (2) access to the malleus and the incus through the wide mastoidectomy, (3) access to the malleus and the incus through the drilled-away tectum. The angular positions were pre-estimated to reduce the measurement time, and the changes of the angular position were quick and of a fine adjustment with the control of the robot arm onto which the stereo camera system was mounted.

At each position of the stereo camera system, cycles of negative (−0.5, −1.0, −2.0, and −3.0 kPa) and positive (+0.5, +1.0, +2.0, and +3.0 kPa) static pressures were provided to the AEC in sequence. At each static pressure step (incl. atmospheric pressure), photos of ossicles were taken by the two cameras of the stereo camera system. All the targeted static pressures could be obtained in 3 out of 5 TBs whereas some of the targeted static pressures could not be reached in 2 TBs (pressure only from −2 kPa to +2 kPa in TB2 and from −0.5 to +3 kPa in TB5 could be obtained). Preconditioning effects have been previously described in literature, with a considerable difference in mechanical behavior between the first and following pressure cycles (e.g., Gaihede 1996; Hüttenbrink 1988).

In the measurements of this study, the negative and positive pressure loads were repeatedly applied to the artificial ear canal to examine possible pressure leaks during the preparation of the sample, and a quick cycle of negative pressures (before measurements with negative pressures loads) or a quick cycle of positive pressures (before measurements with positive pressures loads) was applied before measurements as a preconditioning. Further, all measurements were done in the same order for all samples (i.e., access to the stapes through the wide mastoidectomy, access to the malleus and the incus through the wide mastoidectomy, and access to the malleus and the incus through the drilled-away tectum in sequence; negative pressures first and then positive pressures at each access).

As changes in motion of the ossicles under dehydration could be observed, water mist was sprayed regularly close to the sample to maintain the humidity of the sample. In addition, the sample was submerged in saline solution for >10 min at least every 30 min for reversal of drying effects (Gerig et al., 2015). The total measurement time was less than 2 h including the time for submerging of the sample into the saline solution and the adjustment of the three positions of the camera system.

2.4. Image processing, beads identification and tracking

Once photo images from both cameras of the stereo camera system were obtained for the ossicles at each pressure step, the images were processed to obtain the positions of the fluorescent beads.

First, the images acquired from the stereo camera system were undistorted using the camera parameters obtained during its calibration, i.e., the lens distortion was removed from the images. Then, the images were further enhanced by rendering a grey image of the red channel to enhance the contrast of red fluorescent beads, which were used as tracking markers, to the surrounding structures.

Then, to label the beads in the images, Maximally Stable Extreme Regions (MSER) were extracted. This blob detection method is based on the idea of detecting regions, which stay almost the same through a wide range of thresholds applied on a grey-level set of images. Then, a feature detection algorithm developed by Alcantarilla et al. (2012) named KAZE was used to find accurate centres of the blobs obtained in the previous step. Using this multiscale two-dimensional (2D) feature detection and description algorithm, the centres were detected by means of nonlinear diffusion filtering in a nonlinear scale space, which enables reduced noise and retained image boundaries in comparison to Gaussian feature extraction (Alcantarilla et al., 2012). These obtained blob centre coordinates were then used to label the beads in the images.

The undistorted labeled images (incl. all color channels) were displayed for the left and right camera simultaneously to enable...
the matching of corresponding beads to be tracked between both cameras. For each view, beads were then selected in the first frame (0 kPa), by clicking in the vicinity of a bead and the nearest labeled bead centre was automatically chosen. In the case of a bead not or incorrectly being labeled, the centre of the bead was enlarged and then manually defined. Next, the beads were automatically tracked across the following frames (pressure steps \( \neq 0 \) kPa) by searching for the smallest difference in position to the previous frame. As this was a very simple approach to automated tracking, each tracked point was checked visually across frames and then manually corrected if errors occurred. As the reference markers, i.e., wire ends, were not detectable with the proposed automated tracking algorithm, the locations for these were manually defined in each undistorted picture.

To obtain the three-dimensional (3D) coordinates of the beads and reference markers, the 2D locations of all beads and reference markers in both camera images were triangulated by using the stereo camera parameters obtained in the calibration procedure.

2.5. Registration into anatomical frame and calculation of rigid-body movement

After the measurements using the stereo camera system were completed in each TB, the TB was scanned by a \( \mu \)-CT scanner (\( \mu \)CT40, Scanco Medical AG, Switzerland). The \( \mu \)-CT images of each TB with a voxel size of 18 \( \mu m \) were segmented and 3D features of the ossicles and reference marker wires were generated, using Amira (Version 5.3, Thermo Fisher Scientific, USA). Then, the anatomical coordinate system was defined based on the stapes footplate (origin: the centre of the stapes footplate, +x: anterior; +y: superior; +z: lateral; Sim et al., 2013). Geomagic (Geomagic Design X 5.1 \( \times \) 64, 3D Systems GmbH, Germany) was used in such geometric calculation. Then, as the coordinates of the end of the reference wires in the stereo camera coordinate system were recorded during the measurements using the stereo camera system, correlation between the stereo camera coordinate system and the anatomical coordinate system was obtained using the coordinates of the reference wires in both coordinate systems. An approach of least-square fitting based on the singular value decomposition (Arun et al., 1987) was used to obtain the rotation matrix and the translation matrix of the correlation. Once the correlations between the two coordinate systems were obtained, the 3D coordinates of the fluorescent beads in the stereo camera coordinates system at all the pressure steps were transformed into the coordinates in the anatomical coordinate system.

To define the movements of the ossicles at each pressure step relative to the position under zero pressure, rigid-body movements of the ossicles were calculated. The rigid-body movement could be defined by a 3D rotation and a translation, and the rotational and translational matrices were calculated from changes in the coordinates of the fluorescent beads at each pressure step relative to the position at zero pressure. The least-squares fitting based on the singular value decomposition (Arun et al., 1987) was used in this calculation as well.

Several reference points were chosen for analysis of the ossicular motion: umbo, points on the malleus and the incus at the center of the incudo-malleal joint, points on the incus and the stapes at the center of the incudo-malleal joint and stapes footplate center. Coordinates of these coordinates in the anatomical frame were measured from the 3D volumes of the ossicles obtained from micro-CT images of each sample, and displacements of the reference points were calculated by applying the translational and rotational matrices of the corresponding ossicle to the coordinates of the reference points of the corresponding sample (Figs. 3–8).

For visualization of the 3D movements of the entire middle-ear ossicular chain (Fig. 2 and animations on the web), ‘averaged’ translational and rotational matrices were calculated. The ‘averaging’ across samples was performed using pseudo points, which have the same coordinates in the anatomical frame across samples. 3D movements of the pseudo points were calculated for each of the ossicles in each specimen with the corresponding translational and rotational matrices. Then, position changes of the pseudo points were averaged across the samples, and the ‘averaged’ translational and rotational matrices were calculated with the averaged position changes of the pseudo points.

3. Results

Fig. 2 shows the averaged positions of the human middle-ear ossicles under an EC pressure of –3 kPa (blue) and +3 kPa (red) in comparison to the position at 0 kPa (grey). The averaged position of each ossicle at ±3 kPa was obtained using the averaged translational and rotational matrices of the ossicles (see Section 2.5) across the samples (\( n = 5 \)), and 3D volumes from a sample were used to show the averaged positions of the ossicles. Animations of all movements over all the static pressure steps are provided in the supplemental material (averaged across samples as well). The changes of the ossicular positions relative to the position under zero static pressure in Fig. 2 and animations were amplified by a factor of 5 to visualize the ossicular movement clearly.

Under negative EC pressures, the manubrium of the malleus moved out of the middle ear. A rotational motion around an anterior-posterior axis dominated the motion of the malleus, with the majority of the movement of the umbo in the lateral direction. The rotational axis around the anterior-posterior direction passed through the inferior part of the IMJ. At the IMJ, a gliding motion between the two articular faces was clearly visible, allowing for relative motion between the malleus and the incus. The relative motion between the two ossicles at the IMJ resulted in a smaller motion of the incus and the stapes. As the short process of the incus is firmly anchored by its posterior ligament, a secondary smaller rotation of the malleus-incus complex around the superior-inferior axis passing through the short process of the incus was observed as well. Under positive pressures at the EC, rotation of the malleus around the anterior-posterior axis toward the opposite direction was observed, but the magnitudes were relatively small compared to the rotational motion under negative pressures. Under positive EC pressures, the relative motion between the malleus and the incus at the IMJ was larger than the relative motion under negative EC pressures.

Movements of the stapes under negative EC pressures could be characterized by translation toward the lateral direction and rotation around the long axis of the stapes footplate. The direction of the rotational movement was made such that the stapes head moved toward the inferior direction. The magnitudes of the translational and rotational movements were relatively small compared to the rotational movements of the malleus. Under positive EC pressures, considerable movements of the stapes were not observed with the magnitudes of the applied pressure loads in this study.

The three-dimensional displacement components of the ossicles at five reference points (umbo, point on the malleus at the center of the IMJ, point on the incus at the center of the IMJ, point on the incus at the center of the incudo-stapedial joint (ISJ), stapes footplate center (SFC)) were calculated for more quantitative analysis of the middle-ear ossicular chain (Figs. 3–7).

Fig. 3 displays the displacement components of the umbo. The dominant movement of the umbo was along the lateral-medial direction. The umbo moved laterally under negative EC pressures and medially under positive EC pressures. The magnitudes of displace-
Fig. 2. Averaged \((n = 5)\) position of the human middle-ear ossicles for EC pressures of \(-3\) kPa (blue) and \(+3\) kPa (red) in comparison to position at zero pressure (grey). The displacements were amplified by a factor of 5 to visualize the displacements clearly. Animations of all movements over all the static pressure steps are provided in the supplemental material (averaged across samples as well).

Fig. 3. Displacement components of the umbo along anterior-posterior \((x)\), superior-inferior \((y)\), and lateral-medial \((z)\) directions for EC pressures in the range of \(-3\) kPa to \(+3\) kPa. The central mark (red) indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. “+” in red represents outliers, and the whiskers were extended to the minimum and maximum points in the case that those were not outliers.
ments under negative EC pressures were larger than the magnitudes under positive EC pressures (299 μm at −3 kPa vs. −189 μm at +3 kPa). Though the magnitudes were small, movement of the umbo in the superior-inferior direction was observed as well (−37 μm at −3 kPa and 20 μm at +3 kPa).

The displacement components of the malleus at the center of the IMJ are shown in Fig. 4. For this reference point, mixed movements of the malleus in all three directions were observed under positive and negative EC pressures, without any specific directional motion dominating the others. Along the anterior-posterior direction and the superior-inferior direction, larger movements were observed for negative EC pressures than for positive EC pressures, e.g., the malleus moved 48 μm the in posterior direction at −3 kPa and only 8 μm in the anterior direction at +3 kPa. Along the lateral-medial axis, the malleus moved medially under negative EC pressures and laterally under positive EC pressures. This indicates that the rotational axis of the malleus motion along the anterior-posterior direction is located inferiorly to the center of the IMJ.

Fig. 5 shows the displacement components of the incus at the center of the IMJ. Under negative EC pressures, displacements towards the posterior direction were smaller whereas displacements towards the medial direction were larger than the corresponding displacements of the malleus at the center of the IMJ. The larger displacements of the incus towards the medial direction may indicate that the pivot of the rotational motion of the incus along the anterior-posterior axis is positioned more inferiorly than that of the malleus for negative EC pressures. Along the inferior-superior direction, the two ossicles behaved similarly.

In Fig. 6, displacement components of the incus at the center of the ISJ are shown. At the center of the ISJ, the incus showed move-
ments towards the posterior, inferior, and lateral directions under negative EC pressures and toward the opposite directions under positive pressures. Under negative EC pressures, the inferior motion of the incus at the center of the ISJ increased in comparison to the inferior motion of the incus at the center of the IMJ. Along the lateral-inferior direction, movements of the incus at the center of the ISJ were smaller than movements of the umbo. The lateral movements of the reference point under negative EC pressures were larger than medial movements under positive EC pressures.

Displacement components of the SFC are displayed in Fig. 7. No considerable movements were observed along the anterior-posterior direction or along the superior-inferior direction. Under negative EC pressures, the footplate extruded toward the lateral direction up to 44 μm at −3 kPa, however, no significant movement was observed under positive EC pressures.

4. Discussion

In this study, a method to measure three-dimensional (3D) positions of the middle-ear ossicles in the anatomical frame was established using a custom-made stereo camera system and μ-CT imaging. The established method was applied to obtain 3D displacements of the human middle-ear ossicles in the anatomical frame based on the footplate, when static pressure loads are applied to the EC.

The described method to average 3D movements of the ossicular chain (see Section 2.5) can be problematic in the case the sizes, positions, and 3D orientations of the ossicles in the anatomical frame defined in this study are considerably different across samples. Though non-negligible anatomical differences in the sizes, positions, and 3D orientations of the ossicles in the anatomical frame

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**Fig. 6.** Displacement components of the incus at the center of the incudo-stapedial joint (ISJ) along anterior-posterior (x), superior-inferior (y), and lateral-medial (z) directions for EC pressures in the range of −3 kPa to +3 kPa. The central mark (red) indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. "+" in red represents outliers, and the whiskers were extended to the minimum and maximum points in the case that those were not outliers.

**Fig. 7.** Displacement components of the stapes footplate center (SFC) along anterior-posterior (x), superior-inferior (y), and lateral-medial (z) directions for EC pressures in the range of −3 kPa to +3 kPa. The central mark (red) indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. "+" in red represents outliers, and the whiskers were extended to the minimum and maximum points in the case that those were not outliers.
were observed across the samples used in this study, the averaged 3D motion of the ossicular chain maintained qualitative characteristics of 3D movements of the ossicular chain observed in each of the five specimens used in this study.

The 3D movement of the malleus-incus complex under EC pressures can be characterized by (1) dominant rotational movement of the malleus around the anterior-posterior axis passing through the inferior part of the IMJ, (2) slippage at the IMJ resulting in reduced and complex movements of the incus, (3) larger magnitudes for negative EC pressures than for positive EC pressure in such rotational movement, and (4) small rotational movements of the malleus-incus complex around the superior-inferior axis passing through the posterior incus ligament under negative EC pressures. Hüttenerbrink (1987) stated that the umbo moved almost one-dimensionally along the lateral-medial direction. The results of this study show that such a dominant movement of the umbo along the lateral-medial direction comes from the rotational movement of the malleus around the anterior-posterior axis. Though the rotational movement of the malleus around the anterior-posterior axis is dominant, this study revealed that there exists a small rotational movement of the malleus along the superior-inferior direction, resulting in superior and inferior displacements of the umbo. The superior and inferior displacements of the umbo were observed as well in a study by Dickx and Decraemer (1991, 1992). It was observed in their study that the tympanic membrane at the manubrium is displaced toward the inferior direction under positive middle-ear cavity pressures (corresponding to negative EC pressures in this study), and, with much smaller displacement toward the superior direction under negative middle-ear cavity pressures (corresponding to positive EC pressures in this study). The small rotational movements of the malleus-incus complex along the superior-inferior under negative EC pressures, which were measured in this study, explain such inferior movement of the manubrium in the study. Relatively large displacements of the malleus-incus complex under negative EC pressures compared to the displacements under positive EC pressures were shown in previous works (e.g., Hüttenerbrink 1987; Murakami et al., 1997) as well. The larger displacements under negative EC pressure are presumed to be due to a combination of enhanced stiffness of the tympanic membrane and higher stiffness of the stapedial annular ligament for motion toward the medial direction. A recent study in our lab (under preparation for publication) showed that the annular ligament portrays the highest stiffness when the force is applied toward the medial direction.

The slippage at the IMJ resulting in decreased motion of the incus was observed in several previous works as well. Hüttenerbrink (1988) observed that the relative displacement with the natural IMJ was larger than the relative displacement with the ankylosed IMJ and concluded that the relative motion between the malleus and the incus at the IMJ results in reduced movement of the incus inward/outward (especially inward) under ambient static pressure variation and thus works as a protection mechanism. Ihrlé et al. (2016) observed that two articular surfaces of the IMJ do not impede the rotational motion of the malleus and incus around the anterior-posterior axis under small static loads but show gliding motion between each other resulting in smaller rotational motion of the incus when the static load becomes large. Ihrlé et al. also stated that the gliding motion between the two articular surfaces provide guidance for small relative translational movements between the malleus and the incus along the superior-inferior direction. Stuhlman (1937) stated that the IMJ allows for the relative motion between the malleus and the incus only for their inward movement (i.e., medial under positive EC pressures), not for the outward movement (i.e., extrusion under negative EC pressure). This study also showed that the relative movement between the two ossicles at the IMJ occurred under both negative and positive EC pressures, but it was much larger under positive EC pressure. While the reason for the non-symmetric slippage at the IMJ between the positive and negative EC pressures has not been clearly revealed yet, we hypothesize that the combined reaction of the geometry of the articular surfaces at the IMJ and unequal stiffness of the stapedial annular ligament toward the lateral and medial direction may cause the non-symmetric slippage at the IMJ.

Helmholz (1868) described from his experiments that the gliding motion at the IMJ occurred naturally only when resistance by the stapedial annular ligament was present and disappeared after the removal of the stapes. Considering this, the stapedial annular ligament plays an important role in slippage at the IMJ, and thus unequal stiffness of the stapedial annular ligament toward the lateral and medial directions may cause non-symmetric slippage at the IMJ. Further studies are needed for a confirmation of the hypothesis.

Fig. 8 shows the magnitudes of the medial-lateral displacements of the umbo and stapes, comparing the results of this study with the results from studies by Hüttenerbrink (1987, 1988) and Murakami et al. (1997). The terms ‘intrusion-extrusion’ and ‘inward-outward’ instead of ‘medial-lateral’ were used to define the directions of the displacements in the two reference studies. In the works by Hüttenerbrink, ‘intrusion-extrusion’ and ‘inward-outward’ directions were defined as the direction along the line of movements of the umbo under static pressure loads. As an observation in a previous study that the stapes stands almost vertically on the rotational axis of the malleus and incus (Poltizer 1908; also cited in Hüttenerbrink, 1988), the ‘medial-lateral’ direction defined in this study is presumed to be close to the ‘intrusion-extrusion’ and ‘inward-outward’ directions. The dominant motion of the umbo along the medial-lateral direction from this study (Fig. 3) supports this assumption. The ‘inward’ and ‘outward’ direction were defined as ‘from the middle-ear cavity’ and ‘toward the middle-ear cavity’ without more detailed description. Considering the fact that the displacements of the umbo are dominated by movements along the medial-lateral direction in this study, the ‘inward-outward’ direction in Murakami et al. is presumed not to considerably deviate from the medial-lateral direction of this study. While the static pressure loads were imposed on the EC in this study and the study by Hüttenerbrink, the middle-ear cavity was pressurized in the study by Murakami et al. Focusing on pressure difference across the tympanic membrane, positive and negative pressure loads in the middle-ear cavity can be considered as negative and positive pressure loads in the EC, respectively. The magnitudes of the lateral movements of the umbo under negative EC pressures were similar for all three studies. The magnitude of the extrusion increased in a logarithmic fashion as the magnitude of the negative pressure increased. The same logarithmic behavior was observed as well for the medial movement under positive EC pressures, however, a plateau was already reached at +2 kPa in the study by Hüttenerbrink and our study, i.e., no further increase in displacement could be detected at +3 kPa. In all three studies, the lateral movement of the umbo under negative EC pressures shows larger magnitudes than the medial movement of the umbo under positive EC pressures. For the lateral movement of the stapes head under negative EC pressures, the mean magnitudes from our study were similar to the mean magnitudes from Murakami et al. whereas the median magnitudes from Hüttenerbrink were smaller than the mean magnitudes from the other two studies. The medial movement of the stapes head under positive EC pressures showed much smaller magnitudes than the lateral movement of the stapes head under negative EC pressures both in this study and the study by Hüttenerbrink. However, the magnitudes of the medial movement of the stapes head were even larger than the lateral movement of the stapes head in the data from Murakami et al. This might be due to difference in the application of static
pressures, as pressures were imposed on the middle-ear cavity in Murakami et al., and therefore onto the stapes footplate as well, whereas the pressure was regulated in the EC in the other two studies. The middle-ear joints, especially the IMJ, are presumed to decouple ossicular motion under positive atmospheric pressure variations and thus minimize the medial movement of the stapes into the cochlea as a protection mechanism for the inner ear. In the case of static pressure loads being applied to the middle-ear cavity, the applied pressures directly push the stapes footplate into the cochlea, bypassing the protection mechanism of the middle-ear joints.

Figs. 6 and 7 show reduced movements of the stapes in comparison to movements of the incus at the ISJ. The magnitudes of the displacement components along the anterior-posterior direction and the superior-inferior direction were reduced, and the magnitudes of the medial displacements were reduced as well. Previous studies (Chien et al., 2009; Funnel et al., 2005) suggested that anatomy of the distal incus and the ISJ ‘filtered’ the movements of the incus along the anterior-posterior direction and the superior-inferior direction at the ISJ. While the reduction of the medial component of the stapes motion was not suggested by the two previous studies, the results from this study show that the medial component has much smaller magnitudes than the lateral component. Such smaller magnitudes of the medial component are presumed to be beneficial to protect the inner-ear structures under sudden changes of the ambient static pressure. In Fig. 7, only the footplate center was examined, and the relative magnitudes of the 3D displacement components can be different at other points. However, considering that no significant movement of the stapes was observed under positive EC pressures (Fig. 2 and animation), the benefit for protection of the inner-ear structures is presumed to be valid.

The established method to measure 3D displacements of the middle-ear ossicles in the anatomical frame under EC pressure loads is expected to be applied to surgically reconstructed middle ears as well in the future. The results of this study showed that, in intact middle ears, the medial movement of the stapes into the cochlea was much smaller than the lateral movement of the stapes from the oval window, and thus there exists a protection mechanism for the inner ear as an immediate response. While the protection function of the human middle-ear function was emphasized in the intact middle-ear, measurements of dislocation of prostheses, which may be caused by too large lateral movements of the prosthesis under negative EC pressures, would be important as well for middle ear reconstructions such as ossiculoplasty and stapedotomy.

5. Conclusion

This work provides a method to measure and describe the three-dimensional (3D) quasi-static behavior of the human middle-ear ossicles under static pressure loads in the anatomical frame. Under negative EC pressures, the measured 3D movements of the human middle-ear ossicles showed large rotational motions of the malleus-incus complex around the anterior-posterior axis with slippage of a small amount at the IMJ, and rotational and translational movements of the stapes. Under positive EC pressures, slippage at the IMJ became larger resulting in no considerable movements of the stapes.

The established methods are expected to be applied to 3D movements of the prosthesis in middle-ear implants in the future, with the objective of preventing prosthesis dislocation and damage on inner-ear structures.

Data availability

The link for animation is indicated in the manuscript.
CRediT authorship contribution statement

Birthe Pipping: Methodology, Software, Formal analysis, Investigation, Writing – original draft. Ivo Dobrev: Methodology, Software, Investigation, Writing – review & editing. Merlin Schår: Methodology, Investigation, Writing – review & editing. Michael Chatzimichalis: Methodology, Investigation. Christof Röösli: Methodology, Investigation. Alexander M. Huber: Conceptualization, Supervision, Project administration, Funding acquisition. Jae Hoon Sim: Conceptualization, Writing – original draft, Writing – original draft, Supervision, Project administration.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heares.2022.108651.

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