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Imaging, physiology and biomechanics of the malleus-incus complex

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Purpose: The goal of this study is to establish the biomechanical model of the malleus-incus complex (MIC) based on specific anatomical features of individual ears. Characterization of the malleus-incus complex requires morphological parameters for the bones and soft tissue attachments and their associated material properties. We characterize the isolated malleus-incus complex by combining three-dimensional dynamical measurements and high-resolution microCT based morphology within a biomechanical model features.

Material/Methods: To reduce the complexity of middle ear function and isolate the malleus-incus complex, the eardrum and stapes are dissected by a surgical laser. Without an ear drum, the isolated malleus-incus complex was driven by an electromagnetic field between a tiny magnet attached to the umbo and the coil around the tympanic annulus. The electromagnetic forces are calculated with the dimensional information obtained from microCT scan. Three-dimensional motions of the isolated malleus-incus complex driven by magnet-coil system are calculated from measurement with laser vibrometer. Velocities of several points on the isolated malleus-incus complex, which is attached to two stacked goniometers, are measured from several different angles. Anatomical information of the malleus-incus complex, which is important due to large individual differences, was obtained using high resolution microCT imaging methods. This anatomical information includes typical ligament position, geometric feature of the incudo-malleolar joint (IMJ), and mass distribution of each bone. The described 3D motions were used to estimate parameter values in our anatomically based structural model. In the mathematical model, ligaments were modeled as linear springs and dashpots, and the incudo-malleolar joint was approximated by plane Poiseuille flow. Parameter values of the mathematical model were obtained by Levenberg-Marquardt method applying measured 3D motion to the model.

Results/Conclusion: The Non-destructive imaging method of MicroCT was used to characterize three dimensional features of soft tissues and mass distribution of each bone in the malleus-incus complex. Dimensions and orientations of suspensory cells show significant differences in different temporal bone preparations. Such individual differences in the anatomical features of the middle ear require accurate determination of anatomical information for each specimen. The incudo-malleolar joint has a shape of two orthogonal saddles with maximum gap of 275 μm in the anterior-posterior direction and a minimum gap of 70 μm in the lateral-medial direction. The 3-D motion of the malleus-incus complex driven by magnet-coil system was observed with slippage at the incudo-malleolar joint. For frequencies below 1.5 kHz, the motion of the isolated malleus-incus complex could be represented by a simple rotation about a neutral axis showing a small amount of slippage at the incudo-malleolar joint. At higher frequencies, the malleus-incus complex showed complicated motions with bigger slippage at the joint. Parameter values in our anatomically based mathematical model were obtained with repeated measurements removing elastic components from the malleus-incus complex one by one. The parameter values were consistent with those reported in previous studies. However, the stiffnesses correspond to lower volume fractions of collagen or lower elastic modulus than expected.