On the coupling between the incus and the stapes in the cat

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Abstract

The connection between the long process and the lenticular process of the incus is extremely fine, so much so that some authors have treated the lenticular process as a separate bone. We review descriptions of the lenticular process that have appeared in the literature, and present some new histological observations. We discuss the dimensions and make-up of the lenticular process and of the incudostapedial joint, and present estimates of the material properties for the bone, cartilage and ligament of which they are composed.

We present a preliminary finite-element model which includes the lenticular plate; the bony pedicle connecting the lenticular plate to the long process; the head of the stapes; and the incudostapedial joint. The model has a much simplified geometry. We present simulation results for ranges of values for the material properties. We then present simulation results for this model when it is incorporated into an overall model of the cat middle ear. For the geometries and material properties used here, the bony pedicle is found to contribute significant flexibility to the coupling between the incus and stapes.

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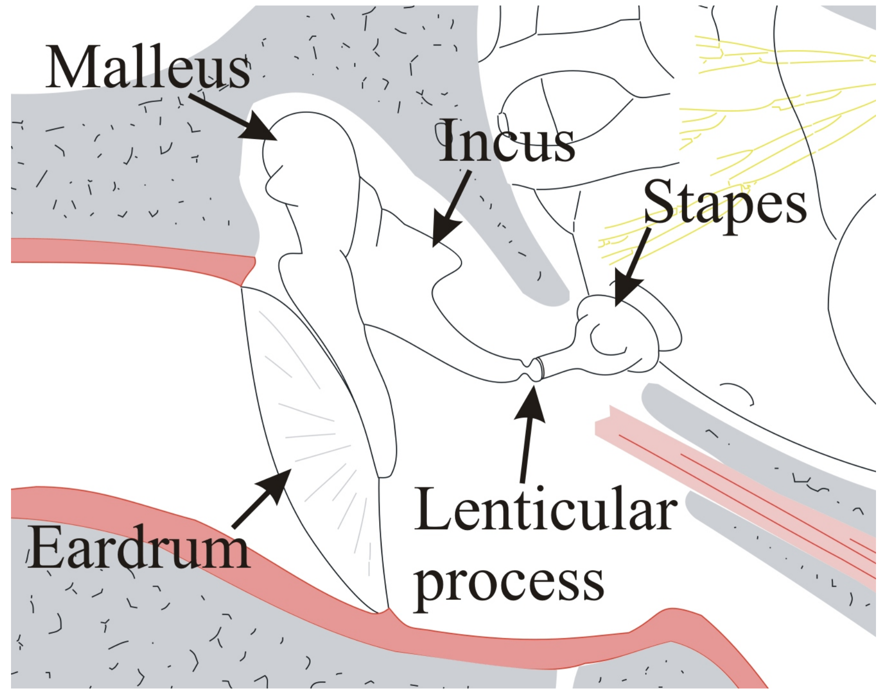
1. Introduction



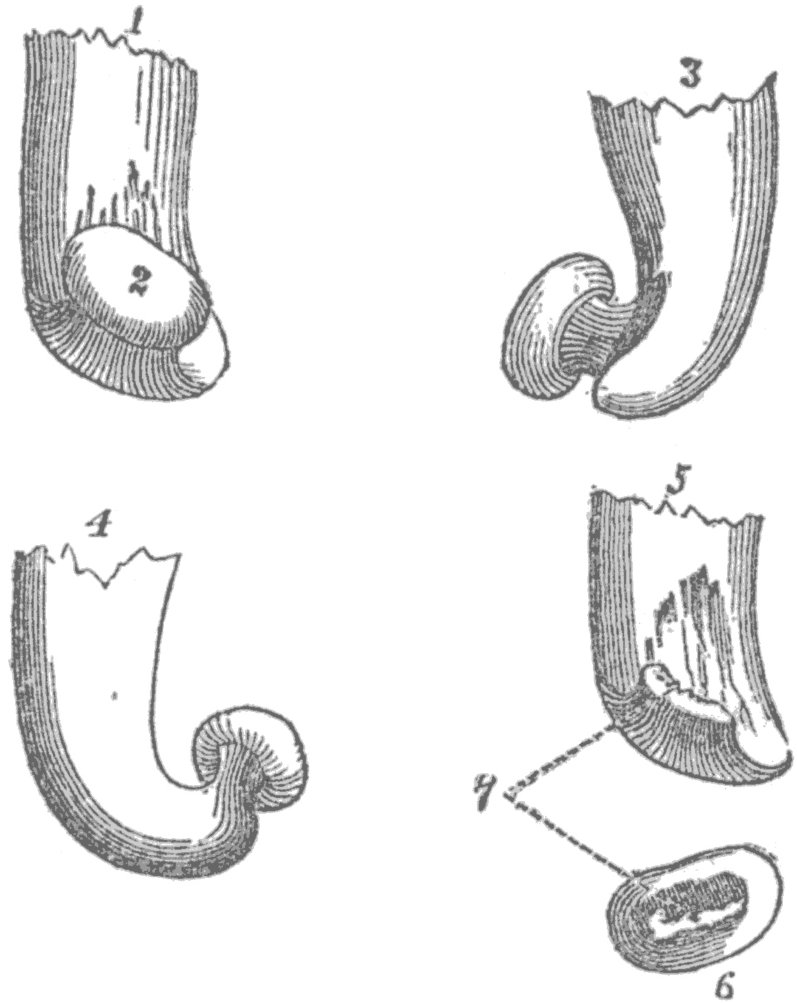
The connection between the long process and the lenticular process of the incus is extremely fine, so much so that some authors have treated the lenticular process as a separate bone. We review descriptions of the lenticular process that have appeared in the literature, and present some new histological observations. We discuss the dimensions and make-up of the lenticular process and of the incudostapedial joint, and present estimates of the material properties for the bone, cartilage and ligament of which they are composed.

We present a preliminary finite-element model for the cat which includes the lenticular plate; the bony pedicle connecting the lenticular plate to the long process; the head of the stapes; and the incudostapedial joint. The model has a much simplified geometry. We present simulation results for ranges of values for the material properties, and then present simulation results for this model when it is incorporated into an overall model of the cat middle ear.

2. Previous descriptions

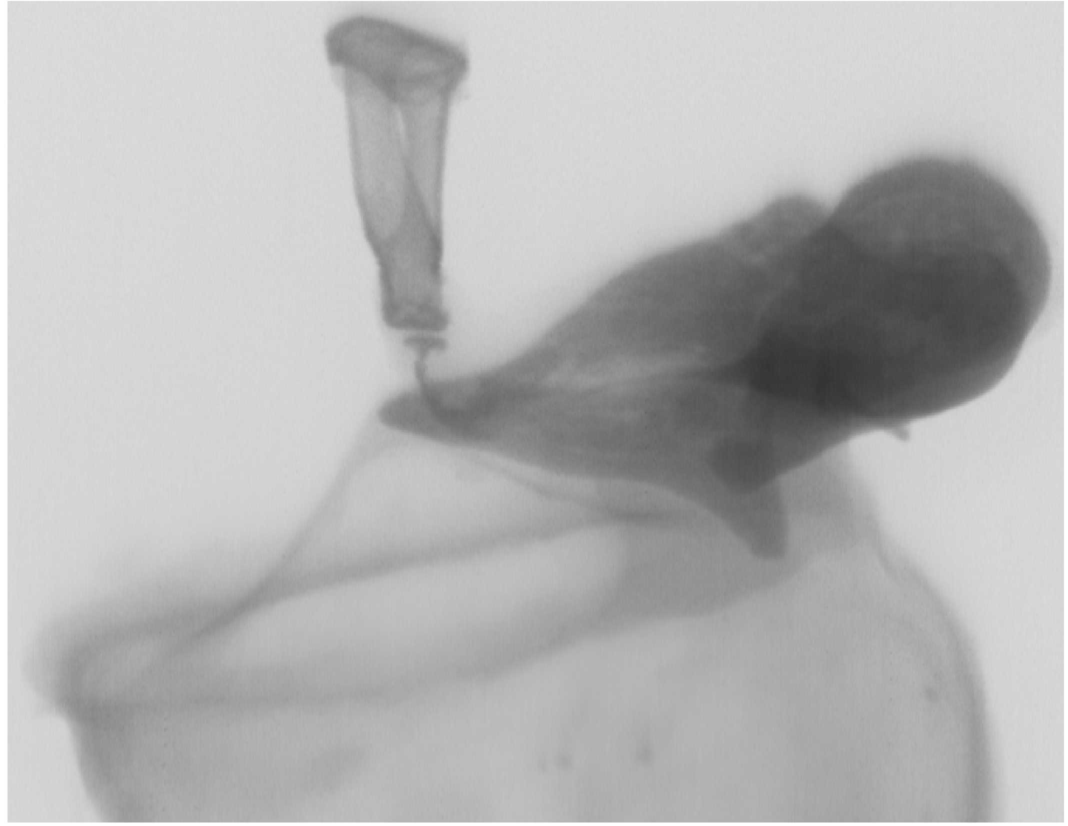
The lenticular process is very small and difficult to observe, and has often been either glossed over or misinterpreted. Asherson (1978) said that the ‘fourth ossicle’, the ossicle of Sylvius between the incus and stapes, was ‘described and depicted in all books on anatomy or otology’ up to about 1900. About 1650, however, Browne wrote ‘Heere you may also see a parcell of the smallest bones, the *incus*, *malleus* & *stapes*, and especially the fourth small bone at the beginning of the *stapes* if you admitt of it with Sylvius for a distinct bone’, which suggests that there was already some doubt.

Shrapnell (1832) observed that the 'most generally received opinion appears to be that it is a separate bone' and proceeded to illustrate convincingly that such is not the case. He clearly showed the bony pedicle joining the lenticular plate to the long process of the incus. The pedicle is shown as four or five times wider in one direction than the other, and somewhat curved.



Eysell (1870) presented a detailed drawing of a histological section, again showing the continuous bony connection.

Before and since these works, the lenticular process has often been described as sometimes (e.g., Wolff *et al.*, 1957) or always (e.g., Palchun & Magomedov, 1997) being a separate bone.



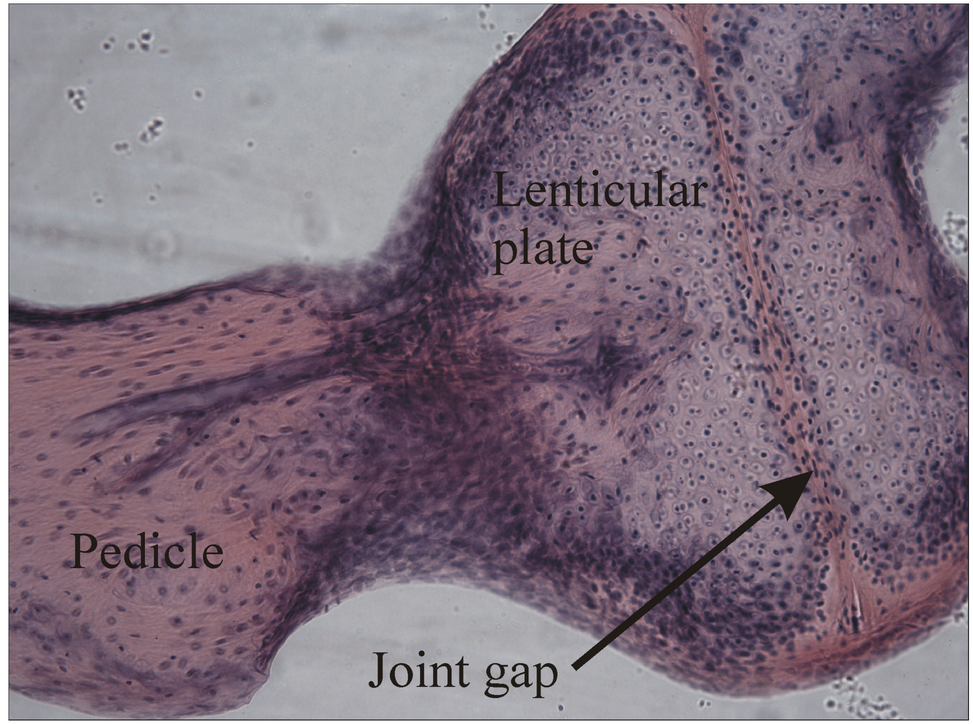
This figure shows a high-resolution x-ray image of a human middle ear (obtained with a SkyScan 1072 microCT machine) showing the narrow dense (apparently bony) pedicle between the incus and the lenticular plate.

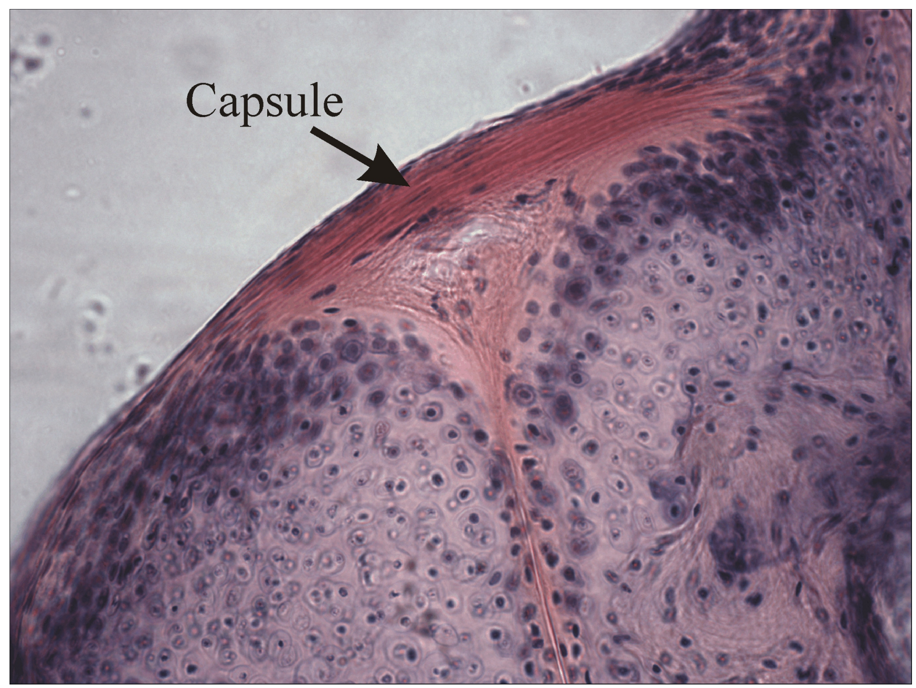
Hüttenbrink (1997) presented a similar x-ray image but the continuity of the connection was not quite so evident.

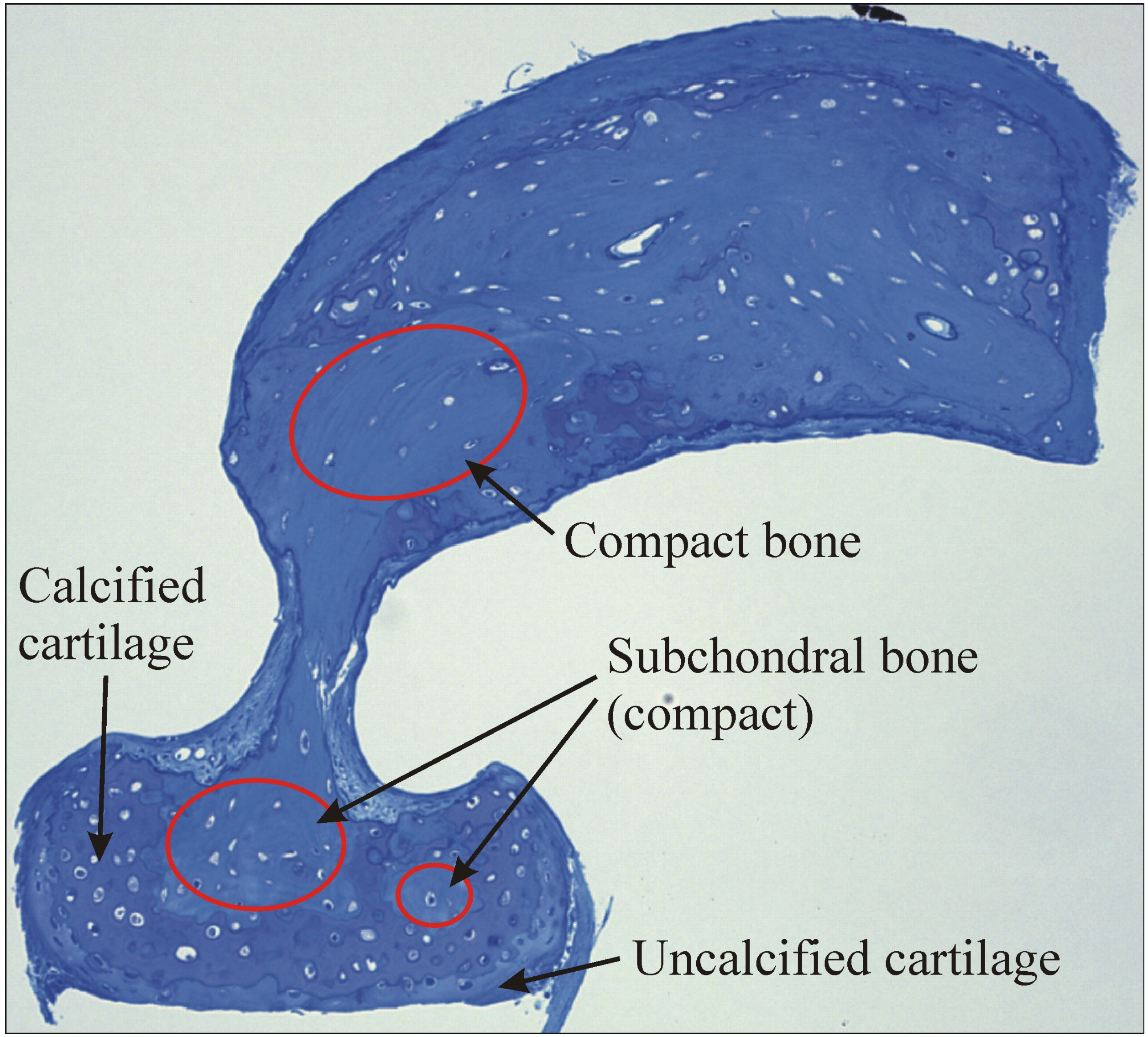
Descriptions of the lenticular process in other species have been few and often unspecific and ambiguous. Among the more detailed are those of Hyrtl (1845), Doran (1878) and Henson (1961). Hyrtl said that 'The Ossiculum lenticulare Sylvii is in no animal an independent ossicle, but an apophysis of the long process of the incus.' Doran referred to it as an apophysis, or perhaps epiphysis, of the incus, and cited the 'beautiful description' by Eysell (1870). Henson described middle-ear structures in three insectivores and eight bats; his overall description of the lenticular process was as 'a small cartilaginous disk mounted on an osseous *pedicle*.'

3. Histology

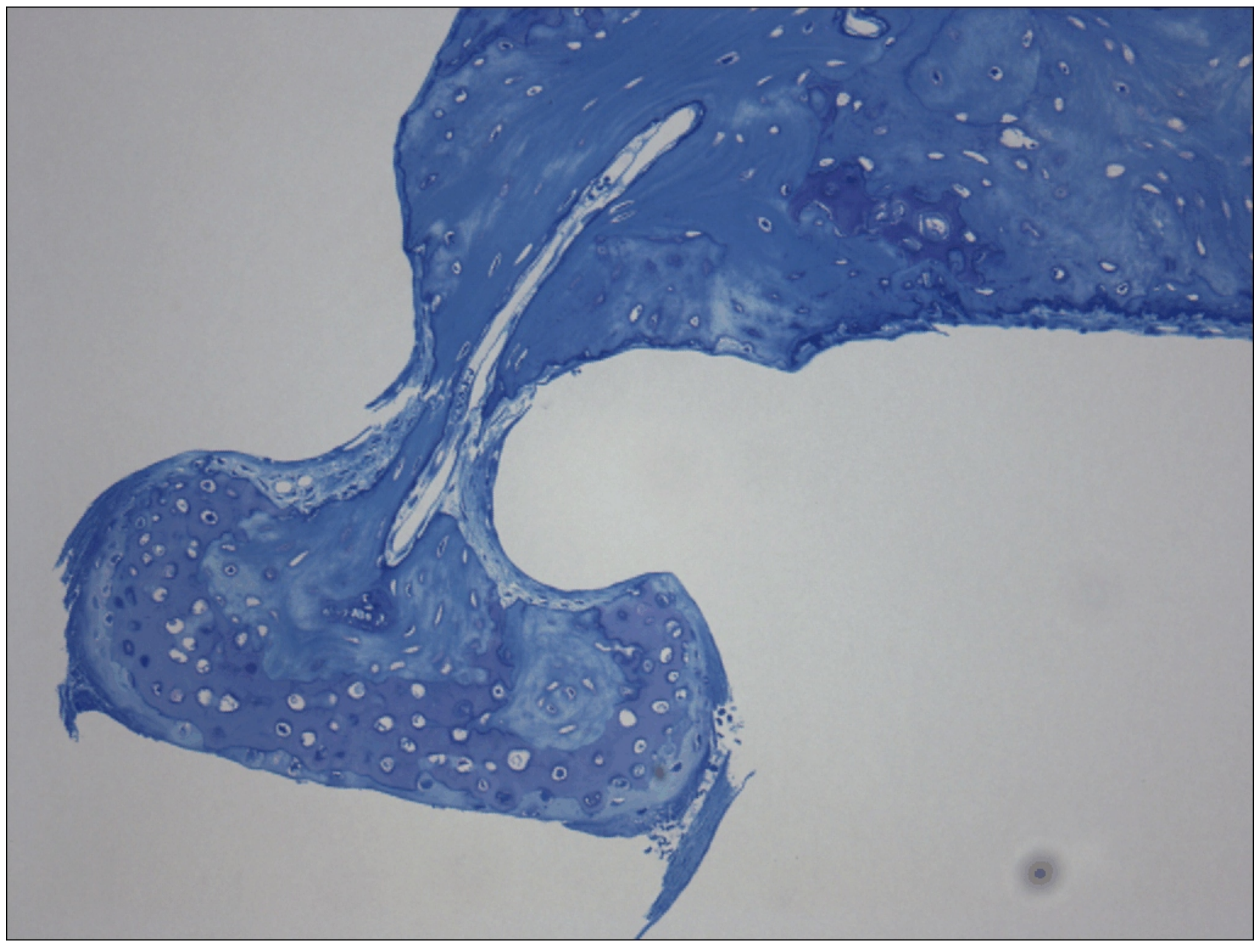
These conventional 20-µm H&E histological sections from a cat ear show the pedicle, lenticular plate, incudostapedial joint space and joint capsule, but the connection between the pedicle and the lenticular plate is unclear.





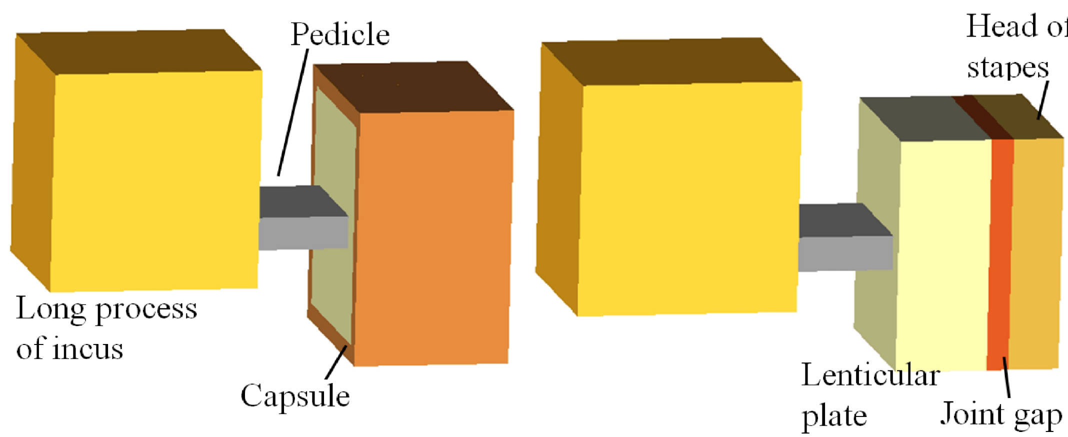


To visualise the cat pedicle more clearly, we have produced a new set of serial sections, cut at 1 µm and with every section stained (toluidene blue) and mounted. This image shows the pedicle (broken during dissection) as a bony connection from the long process to the lenticular plate. The lenticular plate is composed largely of calcified cartilage, with islands of compact bone, and a thin layer of uncalcified cartilage near the articular surface. This slide shows a blood vessel running down the length of the pedicle, exposed outside the bone.

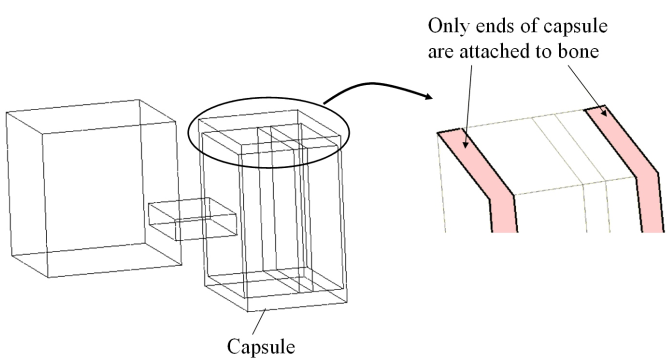


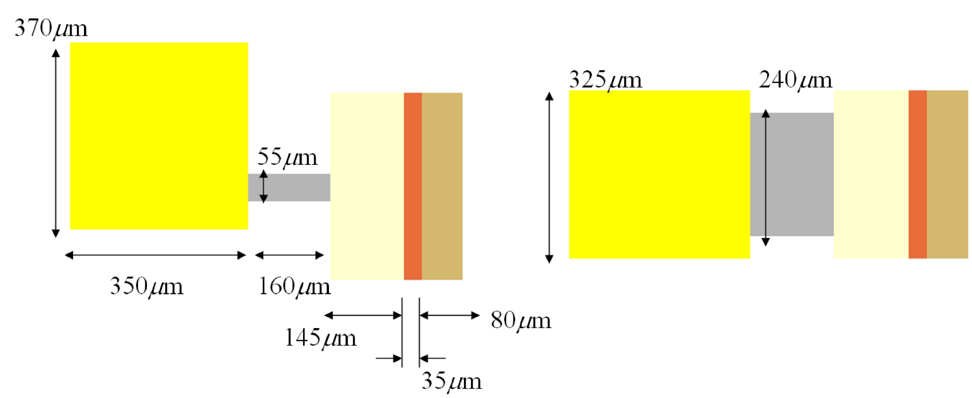
4. Finite-element model

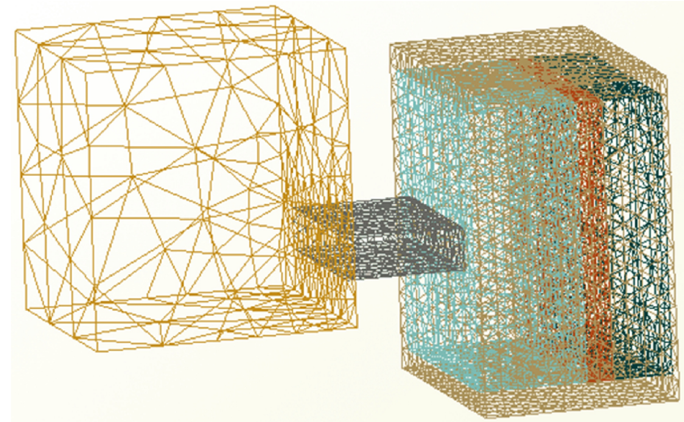
4.1 Geometry. For ease of mesh generation, our current model consists of blocks whose dimensions were estimated from our cat histological sections.



The figures show the model with and without the joint capsule. The detailed dimensions are shown below.





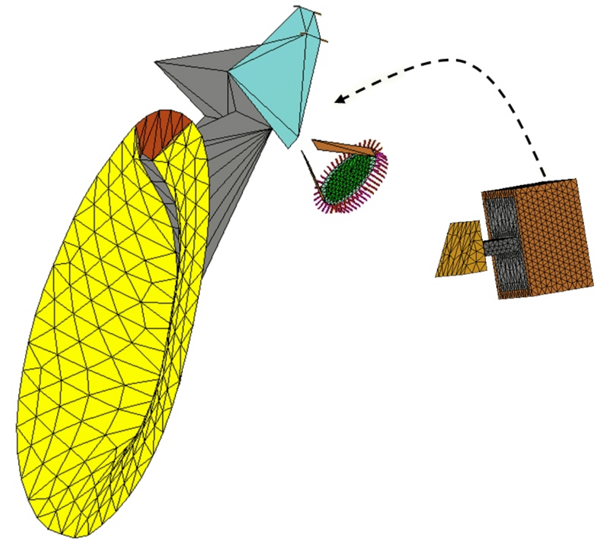


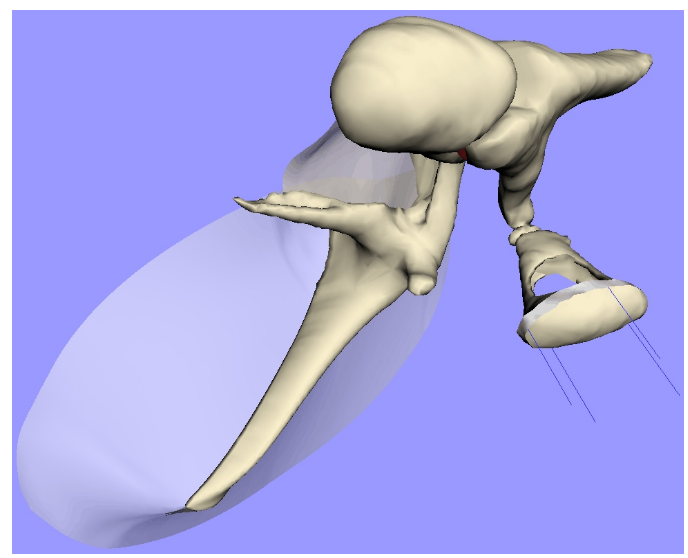
4.2 Material properties. The Young's modulus of bone ranges from 1 to 20 GPa. For the pedicle we have used a value of 5 GPa, as measured for compact subchondral bone by Mente & Lewis (1994). For the joint gap, we assume that the two articulating surfaces are in direct contact, which is the normal mode of function in most joints. We therefore model the gap as cartilage, avoiding the modelling of synovial fluid. We use a Young's modulus of 10 MPa, as measured in normal human articular cartilage (Elices, 2000).

The capsule ligament dominates the overall mechanical properties of the joint capsule. Young's moduli of about 30 to 70 MPa have been reported for shoulder joint-capsule ligaments (Itoi *et al.*, 1993) and values up to 286 MPa have been reported for the hip (Hewitt *et al.*, 2001). We have adopted a Young's modulus of 50 MPa for the ligament.

The lenticular plate and the head of the stapes consist mainly of calcified cartilage and subchondral bone, with Young's moduli of about 0.3 and 5 GPa, respectively (Mente & Lewis, 1994). We have used an intermediate value of 1 GPa.

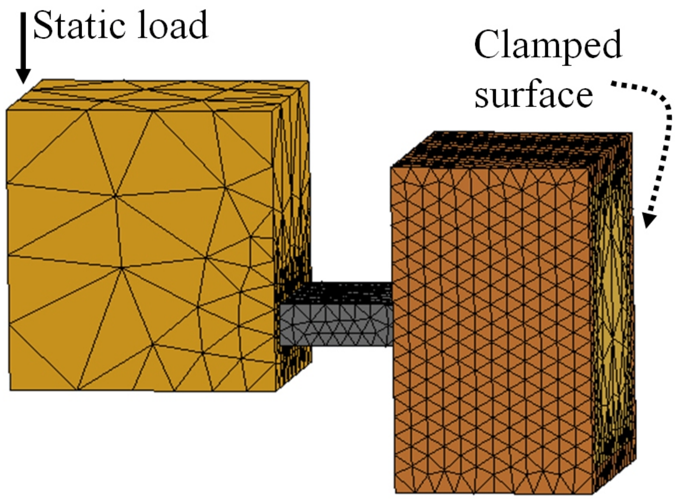
4.3 Overall middle-ear model. For some simulations the lenticular-process-and-joint model was embedded in an overall model of the cat middle ear. The latter model was based on an existing model derived from histological serial sections (Funnell, 1996) revised to reflect orientations seen in a newer model derived from Magnetic Resonance Microscopy data. The figure shows the MRM-based model.

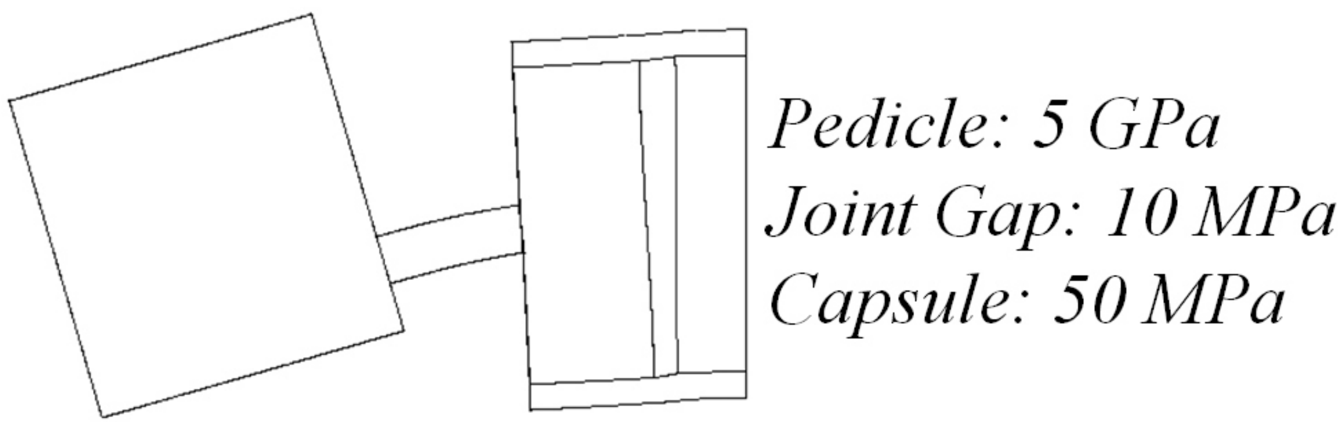




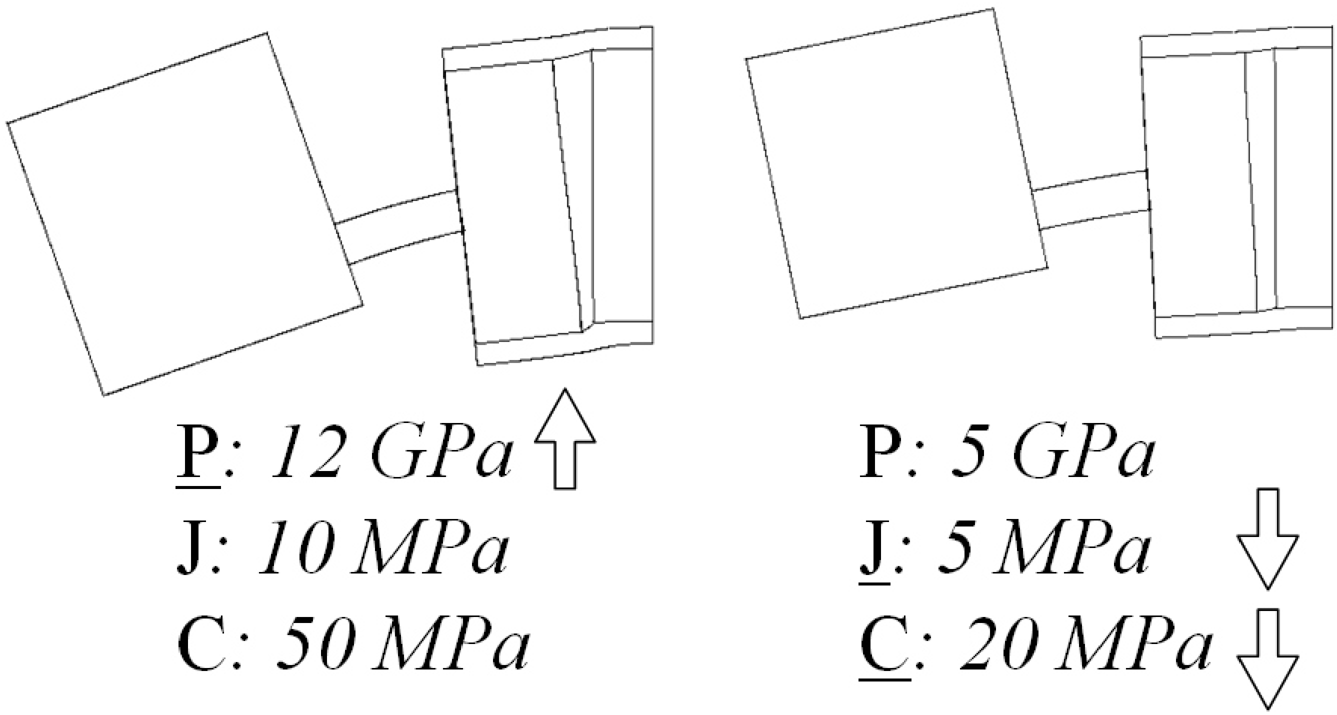
5. Results

5.1 Isolated model. The stapes head was clamped and a static load was applied to the long process. With our estimated stiffness parameters for the pedicle, joint gap and joint capsule, the pedicle undergoes a considerable amount of bending.

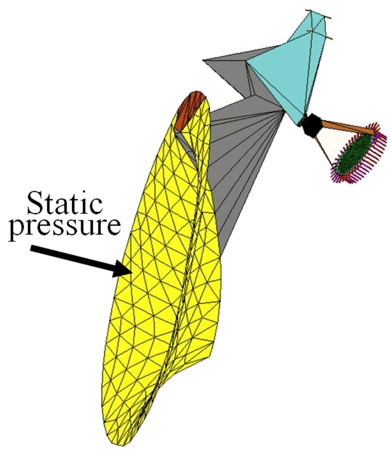




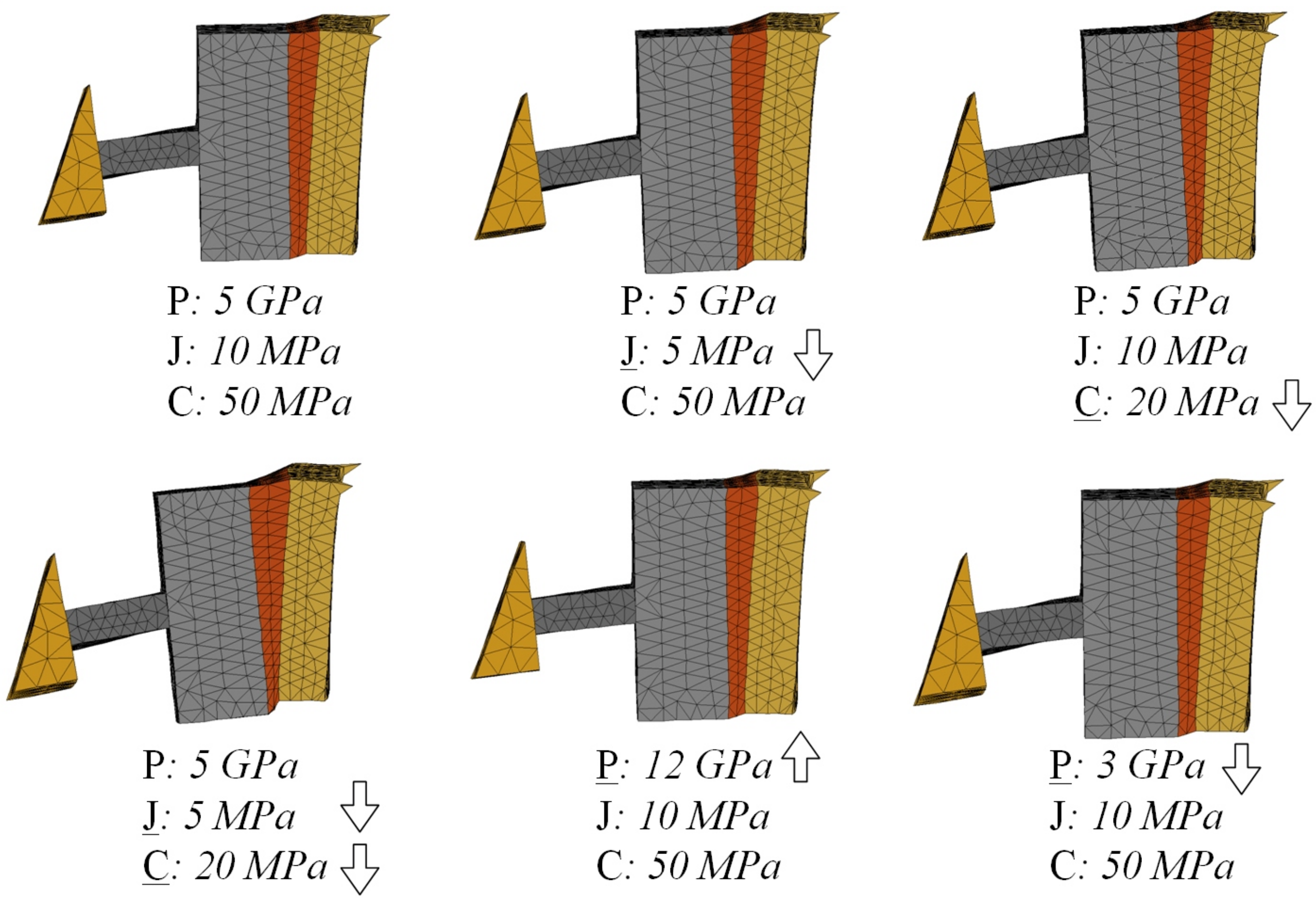
Even if the pedicle is made much more stiff or the joint is made much less stiff, as shown in the figure, the pedicle flexes more than twice as much as the joint does.



5.2 Combined model. The pedicle again flexes more than twice



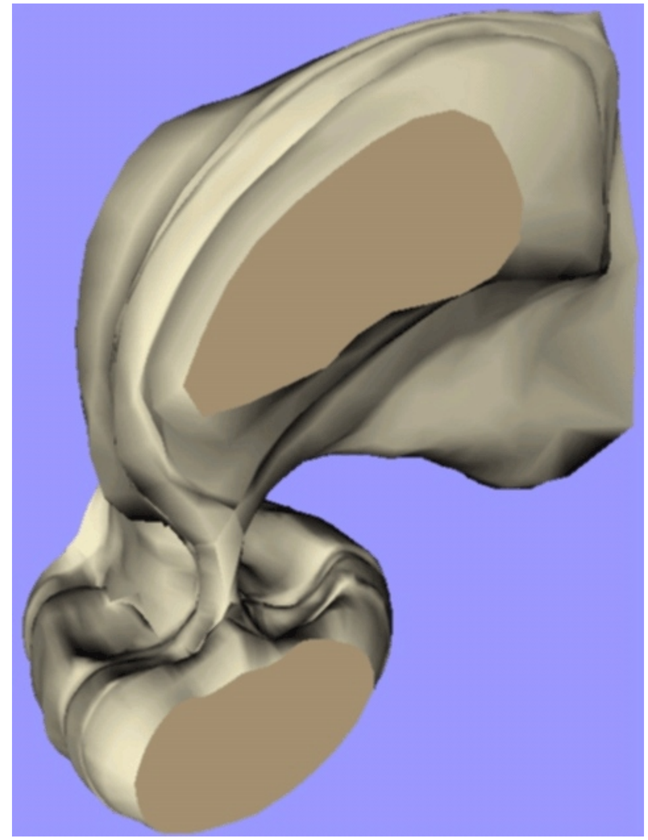
as much as the joint. The pedicle and joint both also twist in response to the pressure on the eardrum.



6. Conclusions

These model results suggest that the bony pedicle between the incudal long process and lenticular plate may provide more flexibility than the actual incudostapedial joint does to the coupling between the incus and the stapes. Because of its particular shape, the pedicle may provide flexibility primarily in a single direction, like a hinge. It seems to be well positioned to convert rotational motion of the incus into translational motion of the stapes.

The delicacy of the pedicle, and the presence of a blood vessel, may have implications for surgical interventions.



Future work will include refining the shapes of the models. The figure shows a preliminary 3-D reconstruction of the pedicle and lenticular plate from our 1-μm histological sections.

The simulations need to be extended to higher frequencies, and a model should be created for the human lenticular process. The range of anatomical variability should also be explored.

It would be very useful to have direct experimental measurements of the incudostapedial coupling.

7. Acknowledgements

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