# Organ of Corti Micromachine Enables Hair Bundles to Deform Basilar Membrane

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Introduction

The organ of Corti (OC) is a highly organized structure in the mammalian cochlea that houses the sensory hair cells. Outer hair cells (OHCs) are cellular force generator that amplifies faint sound stimuli. Two mechanisms for the OHC force generation have been proposed: somatic motility by piezoelectric protein prestin and hair bundle motility driven by mechano-transducer channel. The OC may function to optimize force transmission from the OHC to the basilar membrane. We developed a 3D finite element model of OC to analyze how the OHC forces are transmitted in the OC.

1 The OC is mechanically sustained by inner and outer pillar cells, Deiters cells, OHCs and reticular lamina. Because these cells have well defined primary direction, they were modeled with beam elements. The OC is sandwiched between two acellular membranes—BM and TM, which are represented by framework of beam elements. These membranes have radially arranged collagen fibers. To consider this orthotropy, different Young's moduli were given for radial and longitudinal beam elements of membranes. Geometric data was from the gerbil cochlea at 2 and 10 mm from stapes which encode 25 and 0.4 kHz.
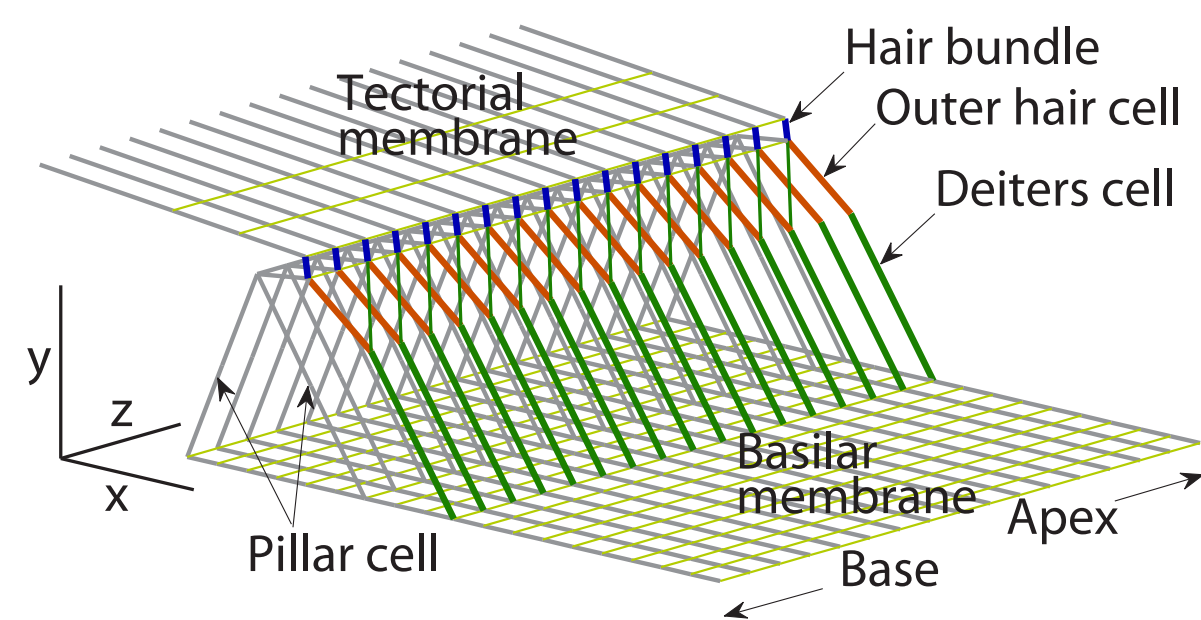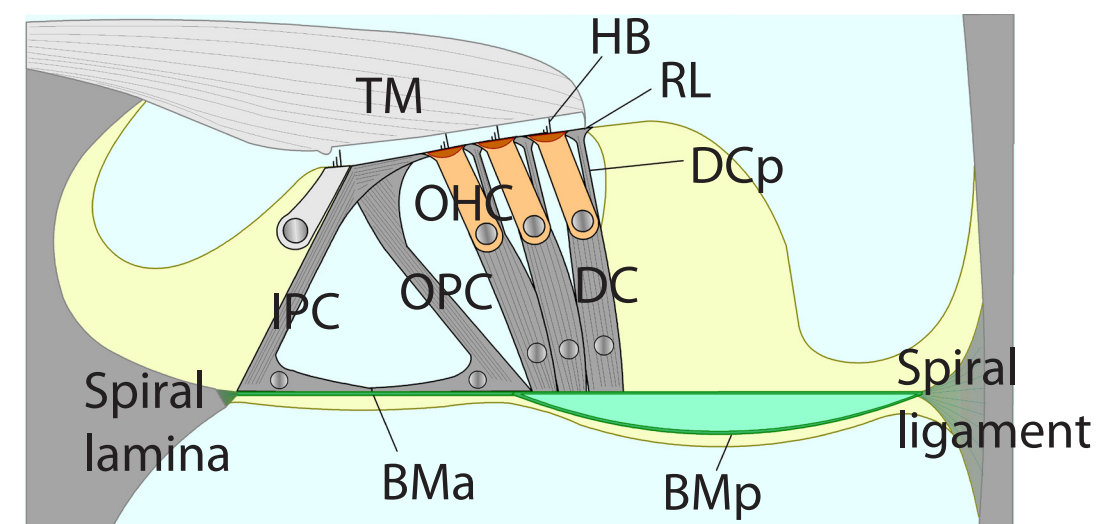

Abbreviations
OC: organ of Corti,   OHC: outer hair cell
HB: hair bundle,   BM: basilar membrane
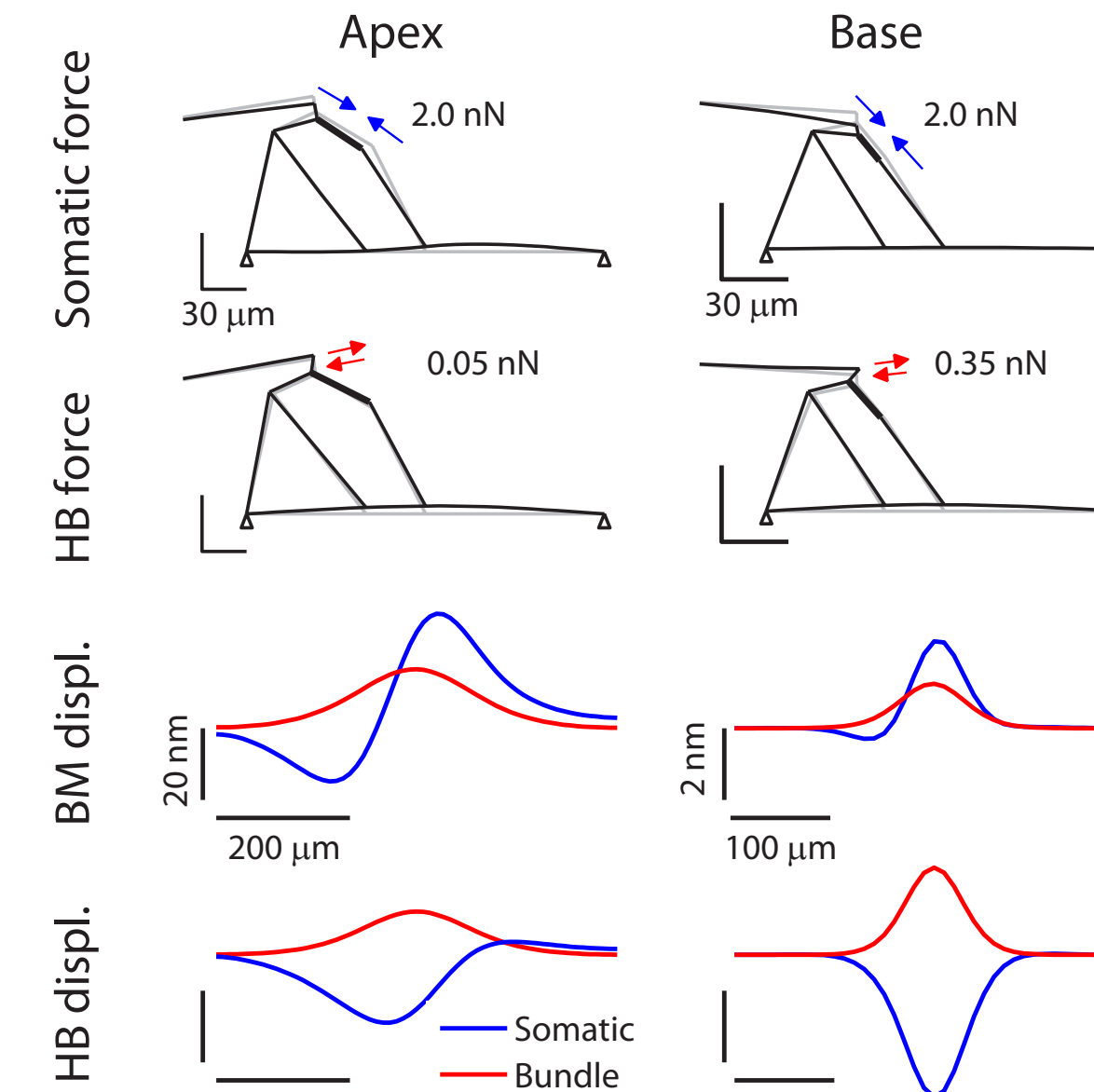RL: reticular lamina,   TM: tectorial membrane

2 OC deformation due to point force applied at the BM. The point stiffness, 0.025 and 1.7 N/m at apex and base, and the longitudinal gradient of point stiffness, 4.4 dB/mm, agree well with experiment results (i.e. Emadi *et al.*, 2004). The extent of longitudinal coupling was represented by space constants which match Naidu and Mountain's measurement (2001).

Apex
0.025 N/m
40 μm   1 nN
λ = 27, 48 μm
○ Whole OC
□ BM only

Base
1.7 N/m
20 μm   1 nN
λ = 11, 18 μm
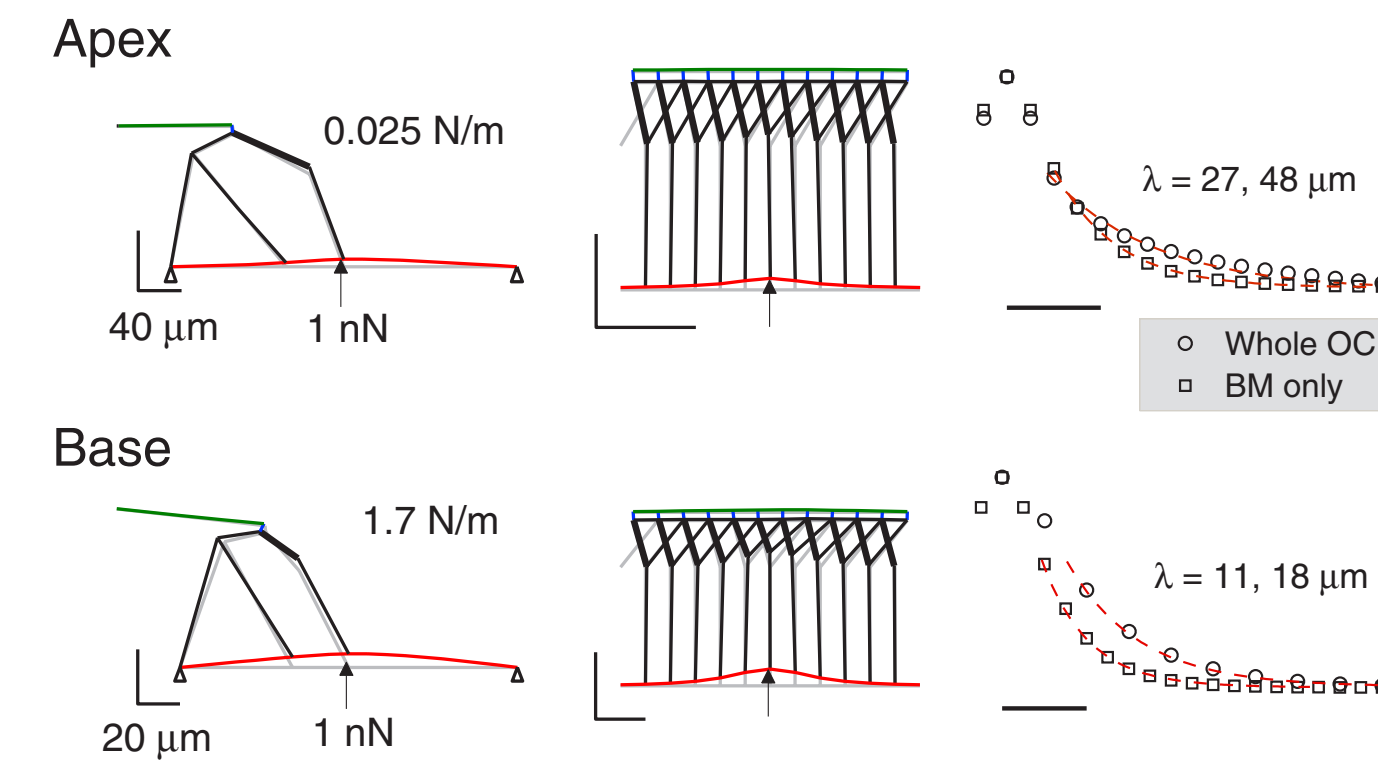
3 OC static deformation mode by OHC somatic force depends on TM stiffness. Measured Young's modulus of TM ranges from 1 to 10 kPa at apex. Within this range, the BM and the RL were displaced in opposite directions by OHC somatic force. Hair bundles were deformed in the negative direction as the OHCs shrink. These deforming modes agree to experimental observations (Mammano and Ashmore, 1993; Karavitaki and Mountain, 2007). However, when there was no tectorial membrane, the deformation mode was different from those experiments.

E_{TM} = 10 kPa E_{TM} = 1 kPa   No TM
30 μm
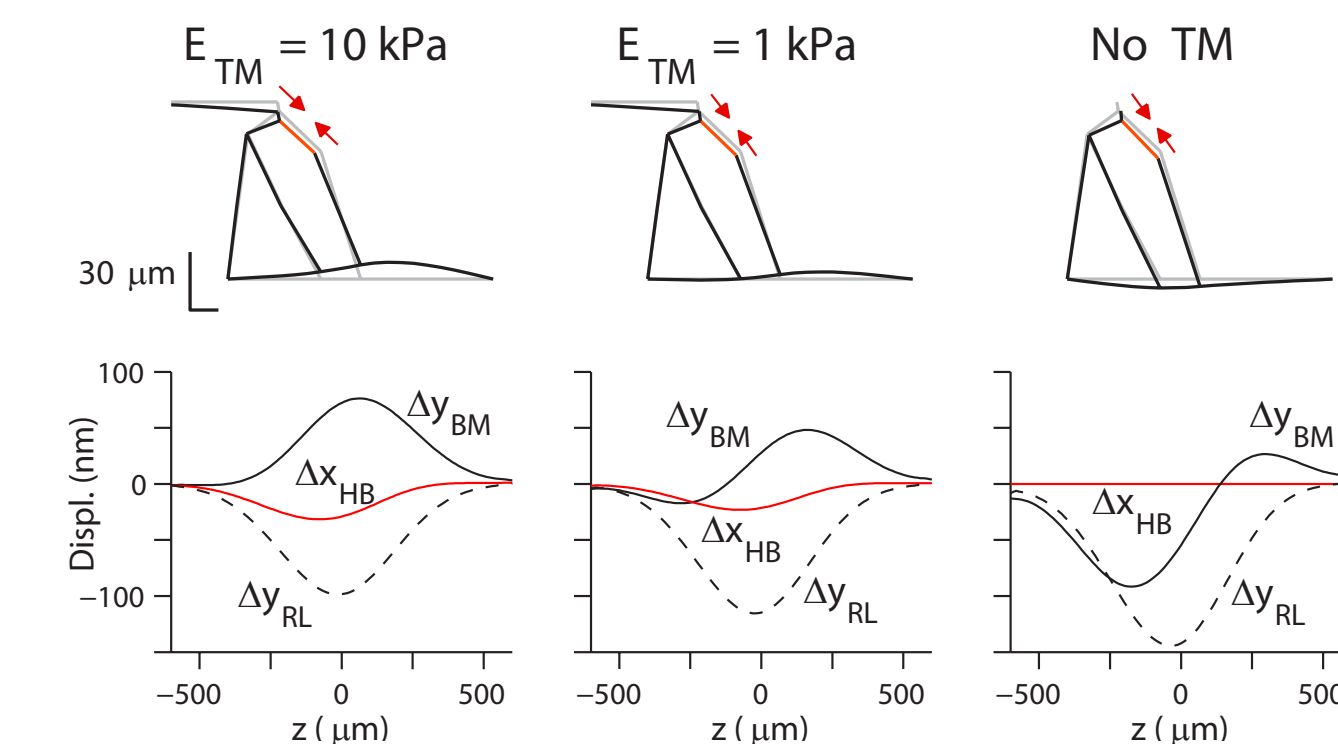
4 Comparison of OC deformation by OHC somatic force and HB force. With 2.0 nN peak OHC somatic force, the BM was displaced by ~20 nm at apex and ~2 nm at base. In order to obtain similar magnitude of deformation, required peak HB force was 0.05 and 0.35 nN at apex and base. Somatic force gave negative feedback to HB displacement.


Apex   Base
Somatic force   2.0 nN   2.0 nN
30 μm   30 μm
HB force   0.05 nN   0.35 nN
BM displ.   20 nm / 200 μm   2 nm / 100 μm
HB displ.
— Somatic
— Bundle

5 HB force is more effective in deforming the BM than somatic force.

$$\mathrm{VG} = \frac{\text{Displaced Volume}}{\text{Pressure}} = \frac{V_{BM}}{f / A_{BM}} \left(\mathrm{mm^4 N^{-1}}\right)$$

	Apex			Base		
E_{TM} (kPa)	10	1	0	200	10	0
VG_{BM}	121	189	333	0.31	0.36	0.39
VG_{OHC}	7	1	-13	0.18	0.02	-0.06
VG_{MET}	253	161	0	0.77	0.27	0

6 Shear gain of OC depends on type of force. Shear gain is defined as $\Delta x_{HB}/\Delta y_{BM}$. Shear gain varied along the location of cochlea and the TM stiffness. Shear gain due to external force at BM ranged 0.2-0.5. Shear gain due to either active force ranged 0.6-2. This predicts that the shear gain for small sound would be greater than the shear gain at louder sound.

Apex   Base
Somatic force
HB force
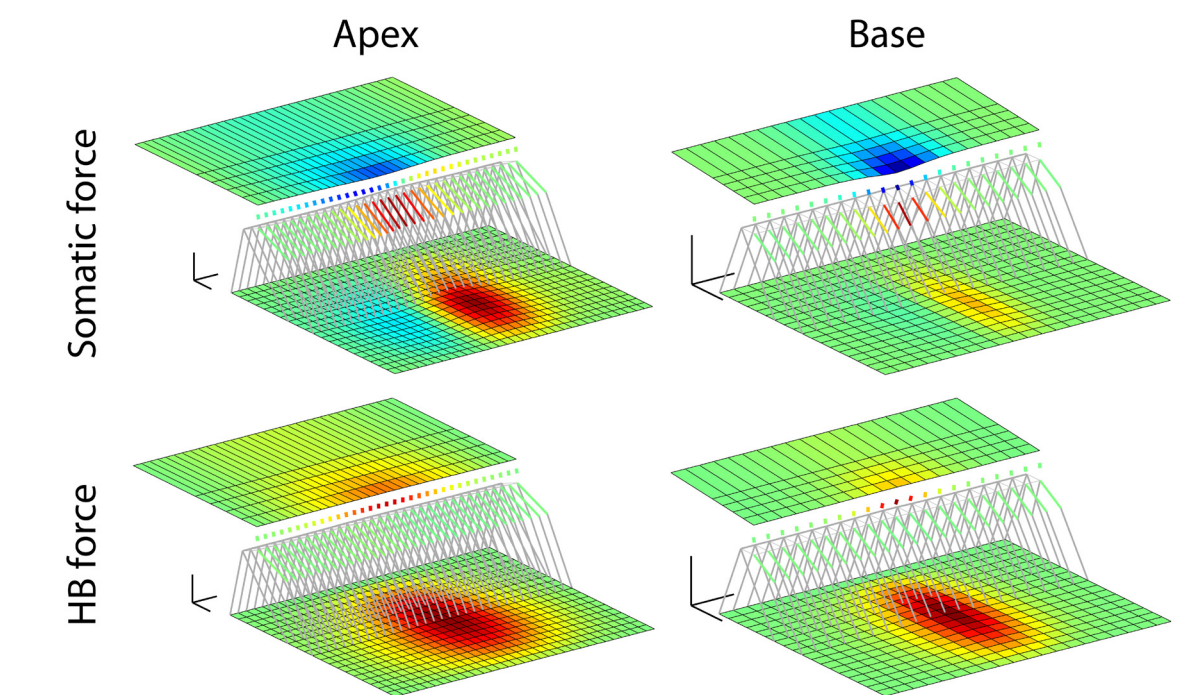
7 OHC somatic force elicited bimodal longitudinal deformation of the BM. Such bimodal deformation was not obvious under BM pressure or HB force. Bimodal distortion originates from longitudinal tilting of OHC and Deiters' cell phalangeal process. When this tilting becomes ignorable, bimodal distortion disappear.

OHC tilt angle   DC process rigidity
0.05 MPa
5.0 MPa
OHC–DCp span   TM rigidity
10 kPa
1 kPa
0 kPa
-100   100 (μm)   Solid lines: Δy_{BM}, Broken lines: Δx_{HB}
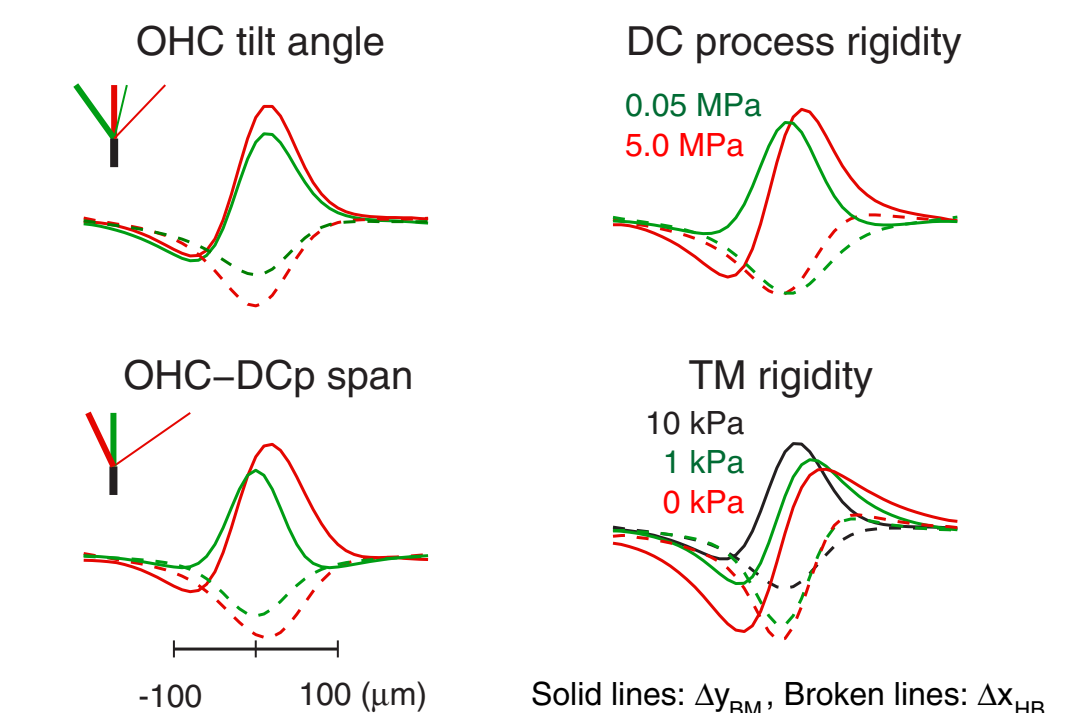
Conclusions

- **Stiff TM helps OHC forces deform BM.**
- **Unlike HB force, somatic force deforms BM and RL in opposite directions.**
- **As OHCs contract, HBs deflect in negative direction.**
- **HB force deforms BM more effectively than somatic force.**
- **OHC somatic force deforms OC rather than BM.**
- **OC shear gain depends on type of forcing source.**