Electronic Supplementary Information

High aspect-ratio deflection transducers inspired by the ultra-sensitive cantilever configuration of scorpion trichobothria

Changchao Zhang,^{‡a} Daobing Chen,^{‡ab} Shichao Niu,^{*a} Junqiu Zhang,^a Xiancun Meng,^a Linpeng Liu,^{ac} Tao Sun,^a Shifeng Wen,^b Yan Zhou,^b Yusheng Shi,^b Zhiwu Han^{*a} and Luquan Ren^a

^a Key Laboratory of Bionic Engineering, Ministry of Education, Jilin University, Changchun 130022, P. R. China.

^b State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.

^c Berkeley Sensor and Actuator Center, Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA.

*E-mail: niushichao@jlu.edu.cn (S. C. Niu); zwhan@jlu.edu.cn (Z. W. Han)

‡ These authors contributed equally to this work.



Fig. S1 (a) The scorpion of *Buthus martesii Karsch* belongs to the *buthidae* family. It is fierce character. The adults is 5-6cm from anal to kiss distance, living in the vast area of East Asia. (b) The trichobothria (Blue arrow pointed) grows on the femur of the scorpion of *Buthus martesii Karsch*. The trichobothria has a slender appearance and a big socket on the base.



Fig. S2 The image of the trichobothria motion special positions was obtained from the screenshots of the video. They are Equilibrium position, Extreme position 1 and Extreme position 2. The max oscillating angle θ can be measured. In the process of the oscillating, the trichobothria does not bend.



Fig. S3 The scanning electron microscope (SEM) images of the trichobothria. (a) Trichobothria on the pedipalp has a long slender hair shaft and relative bigger socket. (b) The shape of the high-aspect-ratio trichobothria is flat. (c) The top part of the trichobothria. (d) The base part of the trichobothria with cylinder shape project into the socket. (e) The cross section of the socket and hair base articulation. hs: hair shaft; bl: lamellae; enc: endocuticle; esw: elongated socket wall; hb: hair base; jm: joint membrane. (f) The fracture surface of the trichobothria on the twisting part. (g) A socket without trichobothria. Scale bar: (a), (b), (d): 100μ m; (c), (e), (f), (g): 2μ m.



Fig. S4 The internal morphological structure of the hair base. (a) The schematic of three different places of the longitudinal section (A-A', B-B' and C-C') of the hair base perpendicular to the hair's plane of oscillation. (b) The schematic of the longitudinal section of the B-B'. The hair base is a helmet structure. The elongated socket wall supports the hair base. The hair base is embraced by the joint membrane. hs: hair shaft; bl: lamellae; epc: epicuticle; exc: exocuticle; enc: endocuticle; esw: elongated socket wall; hb: hair base; rlc: receptor lymph cavity; jm: joint membrane. (c) The section along the C-C' line shows the elliptic hb is embraced by the jm. (d) The hair base is a complete elliptic in the A-A' line section. The endocuticle expands deep into the outer extracellular space becoming the esw and supporting the hb. The yellow box amplification part (e) shows the relative position of hb, exc and the elastic jm. (f) The section along the B-B' line shows the hair base is a helmet structure with a rlc underneath. The helmet is full of lymph and dendrite bundles. The esw also has a cavity here. For that, the dendrite bundle can send the impulse to the central nervous from the cavity. The yellow box amplification part (g) shows that the hb and the esw have a clear dividing line and the cooperating mode. Scale bar: (c), (d), (f): 5µm; (e), (g): 1µm.



Fig. S5 Size relation between diameter of socket and hair. The socket diameter is bigger than the diameter of the trichobothria. It is about 4-10 times. The big socket provides the space for the trichobothria oscillating. D: socket diameter; d: hair diameter; L: hair length. Trichobothria number: N=39.



Fig. S6 Low-frequency sound field. It contains the high-speed cameras, computer, microscopic magnification lens, optical-fiber source, sound tube, loudspeaker, signal generator and supporting.



Fig. S7 The motion state of an 833μ m length trichobothria in the sound filed. (a) The sinusoidal signal (Frequency: 100Hz; Voltage: 50mm/s) generate from the signal generator (GW AFG-2005). (b) The Time-Deflection Angular curve. The maximum deflection angular from the equilibrium position is about 4.5°. The response frequency is about 100Hz. (c) The Time-Angular velocity curve. (d) The Time-Angular acceleration curve. From three motion state curves (b, c, d) we can conclude that the trichobothria is swinging followed by the wind. The three motion state curves (b, c, d) got from the video by motion analysis software Image Pro plus 6.



Fig. S8 Frequency response of a hair with 833µm in length. These movements were measured for sound frequency from 100Hz to 330Hz. The best frequency of this hair is 200Hz.



Fig. S9 (a) Schematic of the stiffness test. It includes an intact trichobothria and a trichobothria fixed with glue base. (b) The femur cut from the pedipalp with a trichobothria extends out. (c) The femur fixed on the glass sheet. (d) A trichobothria was testing on the AFM. (e) The intact trichobothria was tested first, and then the base of the trichobothria was fixed with glue. The fixed trichobothria was tested again. Tr: Trichobothria.



Fig. S10 A force-distance curve. (a) Force-distance curve of 702μ m hair shaft. (b) Force-distance curve of base with fixed 702μ m hair shaft. (c) Force-distance curve of 577μ m hair shaft. (d) Force-distance curve of base with fixed 577μ m hair shaft.

As shown in Fig. S10, *Z* represents the penetration amount of the scanner, which is the sum of the bending amount of the probe cantilever beam and the propping depth of trichobothria, and *Force* represents the restoring force of the cantilever probe (Fig. S11a). As shown in Fig. S10a, the 702µm hair shaft is not fixed. When the probe approaches the hair, the linear shape is straight and there is no non-linear jagged waveform. At this time, the probe is under no load. The probe continues to move downward, the curve appears to protrude, and the thread changes very short, indicating that the Van der Waals force and the hydrophobic force are very weak when the probe is in contact with the surface of the hair shaft. The probe continues to move down. During the process of probe extending and retracting, many non-linear jagged waveforms and unstable points appeared in the curve. These unstable points are presumed to be caused by the uneven elasticity of inner elastic tissues. And the elastic tissues is speculated to contain elastic resilin^{1,2}. There is a large difference in elastic modulus between the elastic tissue and the hair shaft. Because the internal tissue of the trichobothria is composed of a

variety of different materials and structures such as cells, elastin, nerve bundles, and interstitial fluid, the probe will form a sawtooth waveform during the extending and retracting. And larger points of instability may result from transitions between different levels of organization. During the extending process, the curve showed a discontinuous linear change, indicating that the elastic tissues have undergone incomplete elastic deformation and have elastoplastic composite structure. After the probe jumped off the surface of the hair shaft, the curve showed irregular and violent fluctuations, and then suddenly jumped off, with a large jumping thread, indicating that the elastic tissue has good viscoelasticity. Corresponding to Fig. S10a, Fig. S10c also shows similar characteristics of its elastic tissue.

As shown in Fig. S10b, the 702µm hair shaft is fixed. When the probe is close to the hair, the line is straight and there is also no non-linear sawtooth waveform. At this time, the probe is under no load. The probe continues to move downward and suddenly changes. This change is similar to the contact of the probe with the surface of the hair shaft when the hair shaft is fixed. Then the probe continued to move down, the extending line and retracting line were almost straight lines, indicating that there was no other force interference. And the extending line and retracting line almost completely coincide, indicating that the hair shaft are completely elastically deformed, without energy dissipation and plastic deformation. Corresponding to Fig. S10b, after the base of the hair shaft is fixed, the force curve of the hair has the same characteristics regardless of the length of the hair (Fig. S10d). The reason is that after the base of the hair shaft is fixed, the internal elastic tissue does not participate in the mechanical test, and only the mechanical parameters of the hair shaft are tested for the force curve. The material of the hair shaft is single and stable in nature, so it can present a simple force curve pattern without complicated jagged waves. The results show that for different lengths of trichobothria, there is a large difference in the composition of the hair shaft and internal elastic tissue.



Fig. S11 (a) Wind tunnel setup used to test artificial bionic unbending cantilever beams (ABUCB) response. (b) The artificial BUC was made up of elastic silicone rubber with low-aspect-ratio and rigid LDPE with high-aspect-ratio. (c) The cantilevers were loading by airflow. (d) The cantilevers were loading by piece paper. The elastic cantilever was bending naturally by the gravity.



Fig. S12 The deformation is mainly concentrated in the tail of the ABUCB. So the head can be designed into different shapes since meet different test requirements. The image shows the design of the head with different shapes.



Fig. S13 (a) Structure and force analysis of trichobothria. (b) Simplified model and its force analysis. (c) Tumbler structure and force analysis. F: constant force. θ : deflection angle. Cr: the center of rotation. N: external damping force. d: diameter of the bristle rod. Y: distance from the concentrated force on the hair shaft (or tumbler) to the center of rotation. P: support point. R: distance from the center of rotation to the center of mass. H: vertical distance from the constant force F to the center of rotation. h: horizontal distance between the center of rotation and the center of mass. G: gravity of the hair rod (or tumbler). Trichobothria and tumbler have a similar structure, both with a lower center of gravity and a similar center of rotation. At rest, the center of gravity and the support point are on the same vertical line. When subjected to a constant force(The torque generated by this force: F·H), the center of gravity shifts, generating a resistance torque G·h, and an external reaction force N. When the constant force disappears, resistance torque and reaction force return the center of gravity to the same vertical line as the support point.



Fig. S14 Cantilever beam flexible impact test platform. (a) High-speed camera. (b) Experimental support. (c) Water droplet device. (d) Cantilever beam holder. (e) Cantilever beam designed by EDMD principle. (f) Resistance detecting device. (g) Monitor. The water droplets are dropped from 10cm, 20cm, and 30cm respectively. The high-speed camera records the impact state of the water droplet on the cantilever beam and the deflection angle of the cantilever beam. At the same time, the resistance detecting device records the change of the resistance.



Fig. S15 We measured the quality of the water droplets, a total of 100 groups. Through data analysis, the quality of each water droplets is 0.016552g. The energy from the 10cm drop is 1.6221×10^{-5} J. The energy from the 20cm drop is 3.2442×10^{-5} J. The energy from the 30cm drop is 4.8663×10^{-5} J.



Fig. S16 Schematic diagram of electromechanical signal conversion. (a) State of elastic material cantilever under stress. (b) State of rigid material cantilever under stress. (c) State of rigid-elastic coupling material cantilever under stress. (d) The role of rigid material in bionic cantilever. (e) The role of elastic material in bionic cantilever. (f) Schematic of resistance change.

As shown in Fig. S16a, the existing conventional elastic cantilever will be bent under the action of external forces. Its deformation is larger than that of rigid cantilever beam (Fig. S16b), but the change distance L of its tip is also large $(L_1 > L_2)$. This leads to a reduction in the detection range, and the entire beam is used for electromechanical conversion, which makes the cost higher. As shown in Fig. S16b, the rigid material is deflected without bending. The change distance of the tip is relatively small, and its deformation is also small. And the entire beam also is used for electromechanical conversion, which also causes higher cost. As shown in Fig. S16c, rigid-elastic material in bionic cantilever has the advantages of both rigid and flexible beams. At the same time that the change of the tip of the rigid part in bionic cantilever is small, the elastic part of bionic cantilever can ensure a large deformation. The rigid part in bionic cantilever does not deform, that is, it does not consume energy. This ensures that more external mechanical signals are transmitted to the elastic part, making it

easier to perform signal conversion. As shown in Fig. S16d, the rigid part in bionic cantilever is responsible for receiving signals. These signals can be stress signals, chemical signals, optical signals, and so on. When the rigid part receives a signal, it deflects and exerts a force on the elastic part. As shown in Fig. S16e, the crack structure of the groove is easier to adapt to the bending deformation of the elastic part. When the elastic part is bent, the crack structure in the conductive layer is opened and closed, which in turn leads to a change in the overall resistance of the conductive layer (Fig. S16f). Throughout the whole process, the external signal is transmitted to the elastic part without consumption through the rigid part. The elastic part generates a change in the resistance of the conductive layer during the bending process, thereby achieving the electromechanical signal conversion.

Notes and references

- 1 P. Fratzl, F. G. Barth, Biomaterial systems for mechanosensing and actuation. *Nature*, 2009, **462**, 442-448.
- 2 P. H. Brownell and J. L van Hemmen, American Zoologist, 2001, 41, 1229-1240.

Movie 1

The trichobothria oscillate by a slightest movement of the air under the Super Well Depth Microscope (VHX-2000). The frame rate set is 50fps. The trichobothria has been amplified 40 folds.

Movie 2

The fresh cut pedipalp with an 833µm trichobothria oscillates in the sound field at frequency 200Hz and air peak velocity 80mm/s. The frame rate set is 6000fps. The trichobothria has been amplified 40 folds. The playback speed is 20 frames per second.

Movie 3

A BUC oscillates by the movement of the air. The shaft length is 40mm, and the diameter is 1mm. The frame rate set is 30fps.