Supplemental Material for

Optimal kinematics of a bee tongue for viscous fluid transport

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Tongue morphology

To observe morphology of bee tongue (*Apis mellifera* L.), we dissected the mouthpart of workers (n=4 samples). The samples were fixed for 3 h by a 2.5% glutaraldehyde solution and then dehydrated in an ethanol series of 75%, 80%, 85%, 90%, 95%, and 100%, coated in gold-palladium (50 nm) [1,2]. As shown in Fig. S1A and S1B, we obtained the morphology of the hairy tongue under a scanning electron microscope (Hitachi S-3400N, Japan). The geometries, including radius of the tongue body R_T, length of tongue hair L_H, and diameter of tongue hair d_H, were measured and plotted in Fig. S1C and S1D. The tongue turned thicker from the distal end to the proximal part as the radius of the tongue body was fitted as $R_T(x) = 44.17x + 42.81$ μm (R^2=0.96, x: mm). The average radius of the region where the hairs are located ($x_1 = 0.02$ mm and $x_2 = 1.19$ mm) is $\langle R_T \rangle = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} R_T(x)dx \simeq 70$ μm. The length L_H and diameter d_H of tongue hair also vary slightly along with the bee tongue axis according to $L_H(x) = 41.02x + 157.03$ μm (R^2=0.99) and $d_H(x) = 0.80x + 2.46$ μm (R^2=0.97). Therefore, the average length and diameter of tongue hairs in the measurement area can be calculated by $\langle L_H \rangle = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} L_H(x)dx \simeq 180$ μm and $\langle d_H \rangle = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} d_H(x)dx \simeq 3$ μm, respectively.

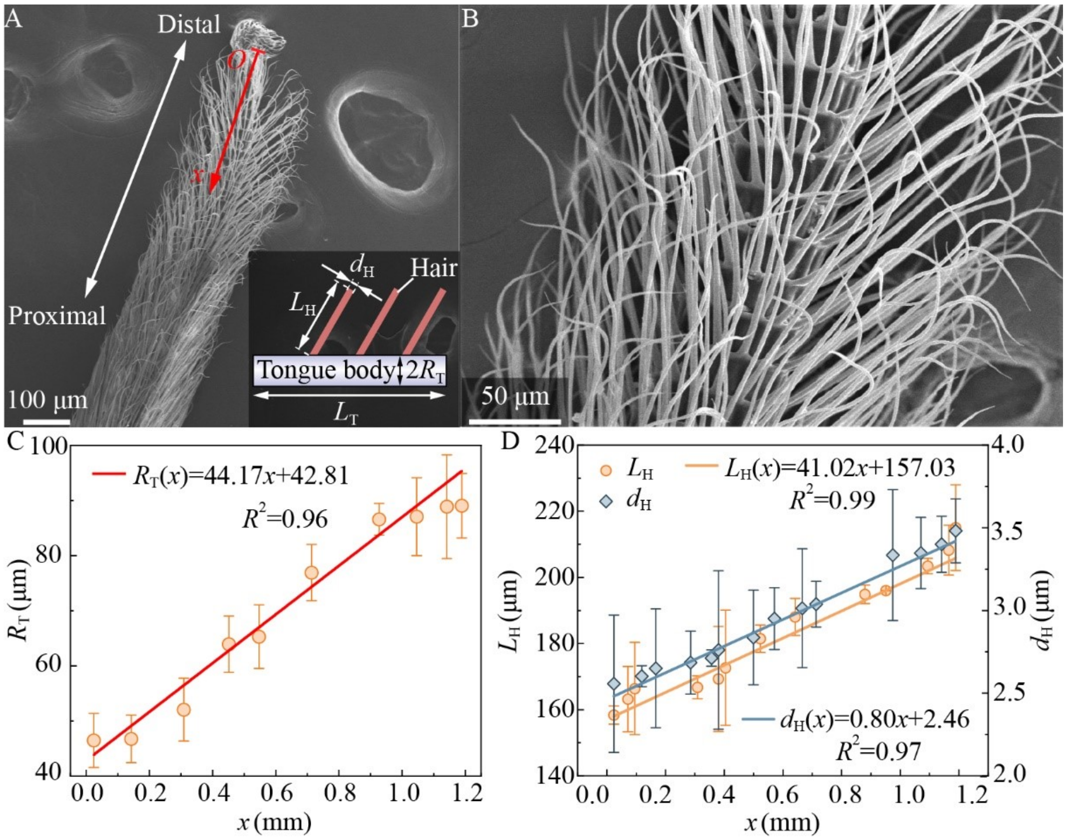

Fig. S1 Morphology of a bee tongue (*Apis mellifera* L.). (A) SEM image shows the full view of the bee tongue. Inset: Schematics for measuring tongue geometry. (B) Zoomed-in view of the middle part of the tongue with dense hairs bearing on each segmental ring of the tongue. (C) Variation in radius R_T of the tongue body alone the tongue axis. (D) Diameter d_H and length L_H of tongue hairs on different locations of the bee tongue.

Erection dynamics of the tongue hairs

To quantify kinematics of the bee tongue while drinking 35% sucrose solution, we first recorded the dipping process under a microscope (Olympus, CX33, Japan) equipped with a high-speed camera (VEO 310 L, Phantom, USA). The frame rate was 1000 fps, and the image size was 1280 pixels × 800 pixels [3,4]. A coordinate *O*-*x* was fixed on the tongue tip, which was motionless in nectar-feeding (Fig. S2A). As shown in Fig. S2A, we selected the three positions of the bee tongue, namely A, B, and C, which was 450 μm, 900 μm, and 1350 μm away from the tongue tip. We measured the tongue diameter $D(t)$ at three positions, as shown in Fig. S2B. The distance between the hair tip and tongue body at three positions was thus computed by $d(t) = D(t) - 2R_T$, where the radius of tongue body R_T was given by $R_T = 44.17x + 42.81$ μm (Fig. S2C) [5].

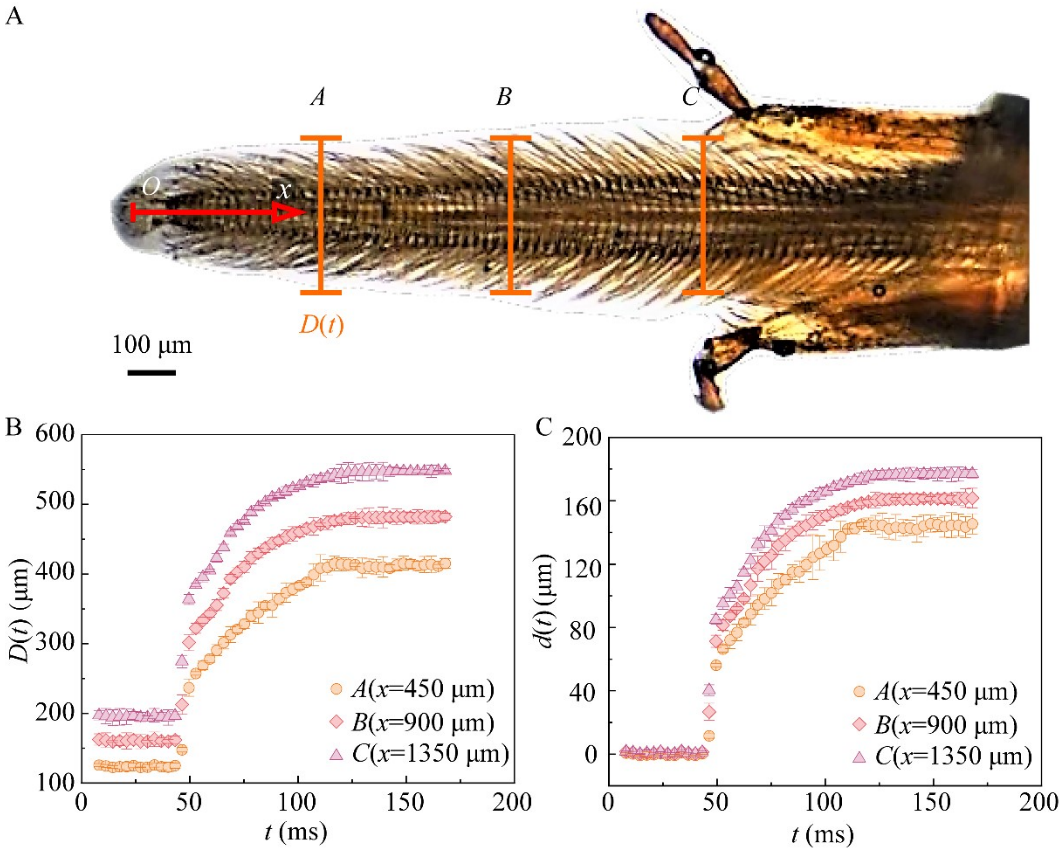

Fig. S2 (A) Snapshot for dipping 35% sucrose solution shot at 60 ms after the protraction starts. (B) Tongue diameter $D(t)$ with respect to time t. (C) The temporal variations of the distance $d(t)$ between the hair tip and surface of tongue body during dipping.

Table S1. Extended data for body masses and dipping kinematics for six bee species.

Species	Samples	m (mg)	L_T (mm)	R_T (μm)	ψ	T_2 (ms)
Trigona ventralis S.	1	12	1.9±0.1	31±6	69±2	274±21
	2	13	1.8±0.2	26±10	68±3	250±20
	3	12	1.6±0.1	31±8	68±4	210±56
	4	14	1.8±0.2	27±9	69±3	242±53
Ceratina flavipes V.	1	24	2.2±0.2	41±6	66±3	236±34
	2	20	2.3±0.1	40±10	67±5	225±73
	3	34	2.2±0.2	35±5	69±3	222±44
Nomia. strigata F.	1	52	2.0±0.2	51±7	66±2	206±24
	2	37	2.1±0.1	42±6	63±4	207±64
	3	45	2.1±0.1	40±6	67±4	208±66
	4	36	1.9±0.1	51±8	59±3	195±69
Apis. cerana L.	1	89	2.2±0.1	49±6	62±3	186±38
	2	95	2.3±0.2	58±5	61±4	177±91
	3	79	2.3±0.1	62±5	60±3	186±66
	4	92	2.3±0.2	56±10	61±2	172±41
	5	95	2.4±0.1	53±10	60±3	182±68
Apis mellifera L.	1	105	2.7±0.3	74±8	67±2	153±30
	2	113	2.6±0.2	79±6	60±2	114±14
	3	88	2.6±0.1	67±6	60±3	124±25
	4	94	2.7±0.3	77±9	59±3	190±62
	5	101	2.6±0.1	62±8	56±4	135±27
Bombus. Terrestris S.	1	375	3.9±0.1	113±10	50±4	92±13
	2	307	4.8±0.1	108±9	55±3	100±52
	3	435	4.6±0.1	106±15	53±2	112±16
	4	492	3.8±0.2	102±8	52±3	117±26
	5	456	4.2±0.2	103±11	61±3	124±21

References

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