Oscillation of the velvet worm slime jet by passive hydro-dynamics instability

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Maryland University, March, 2015

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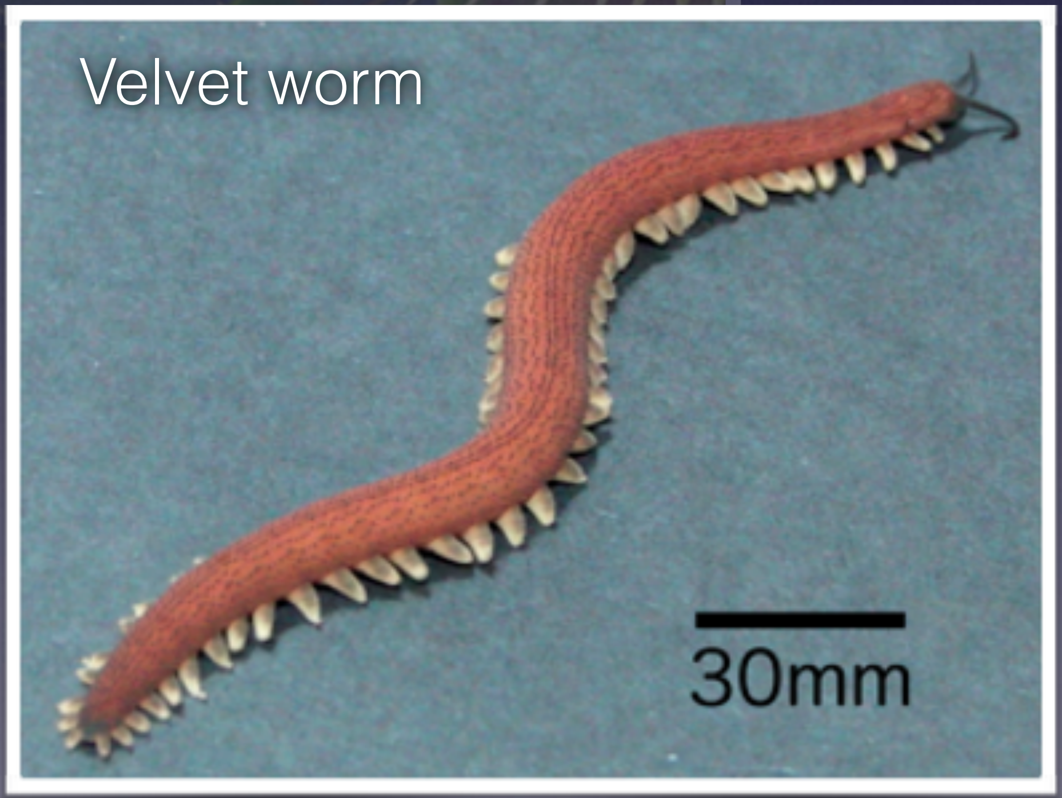
Rapid motion in nature for scape and predation



The velvet worm projects itself by squirting a jet of slime in an oscillatory fashion, not only for capturing prey, but also for defense

Rapid squirt of a proteinaceous slime

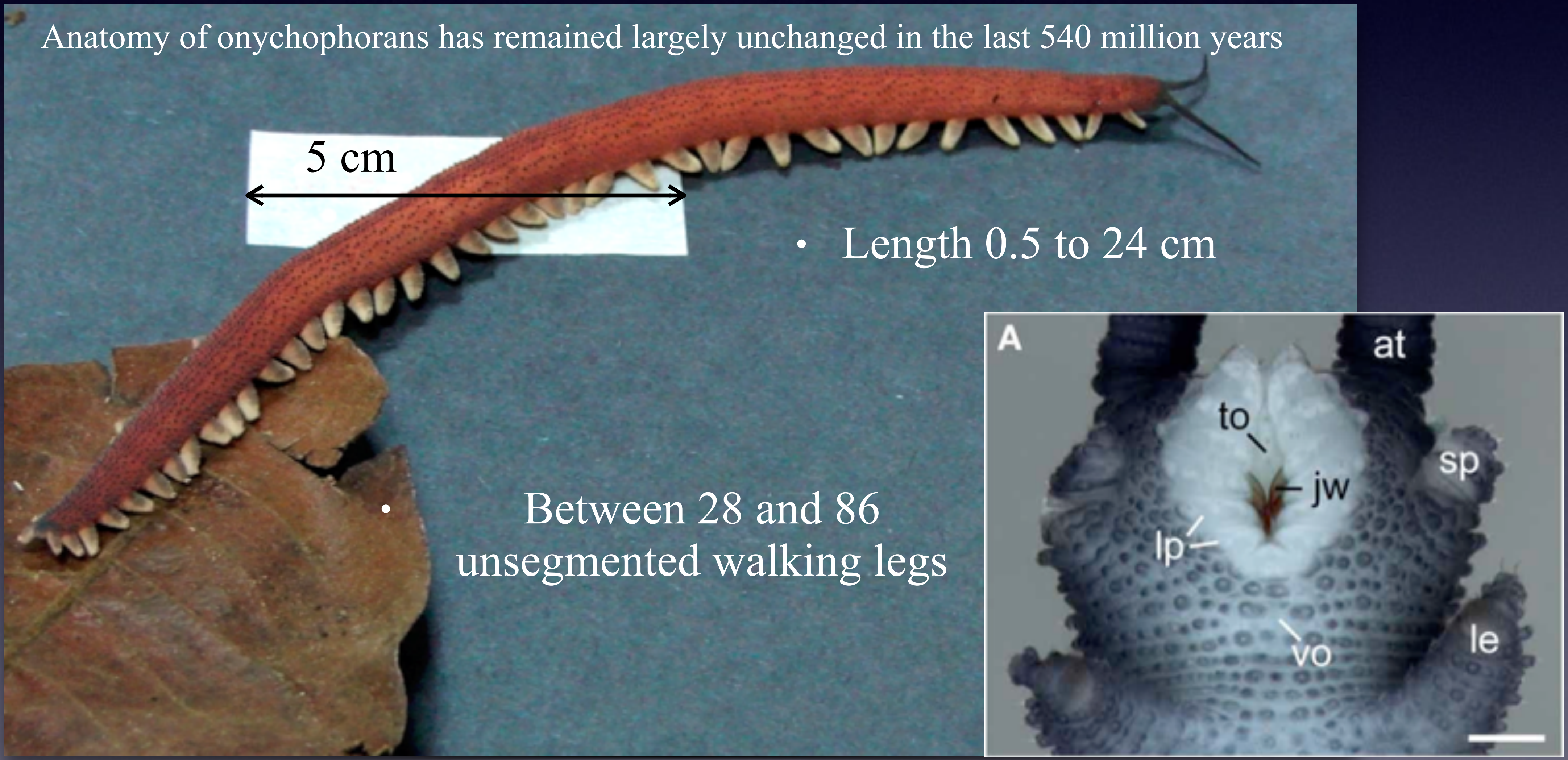
Jets are directed in a straight line in most animals.

Exceptions: velvet worms (Phylum Onychophora),

spitting spiders, and spitting cobras.

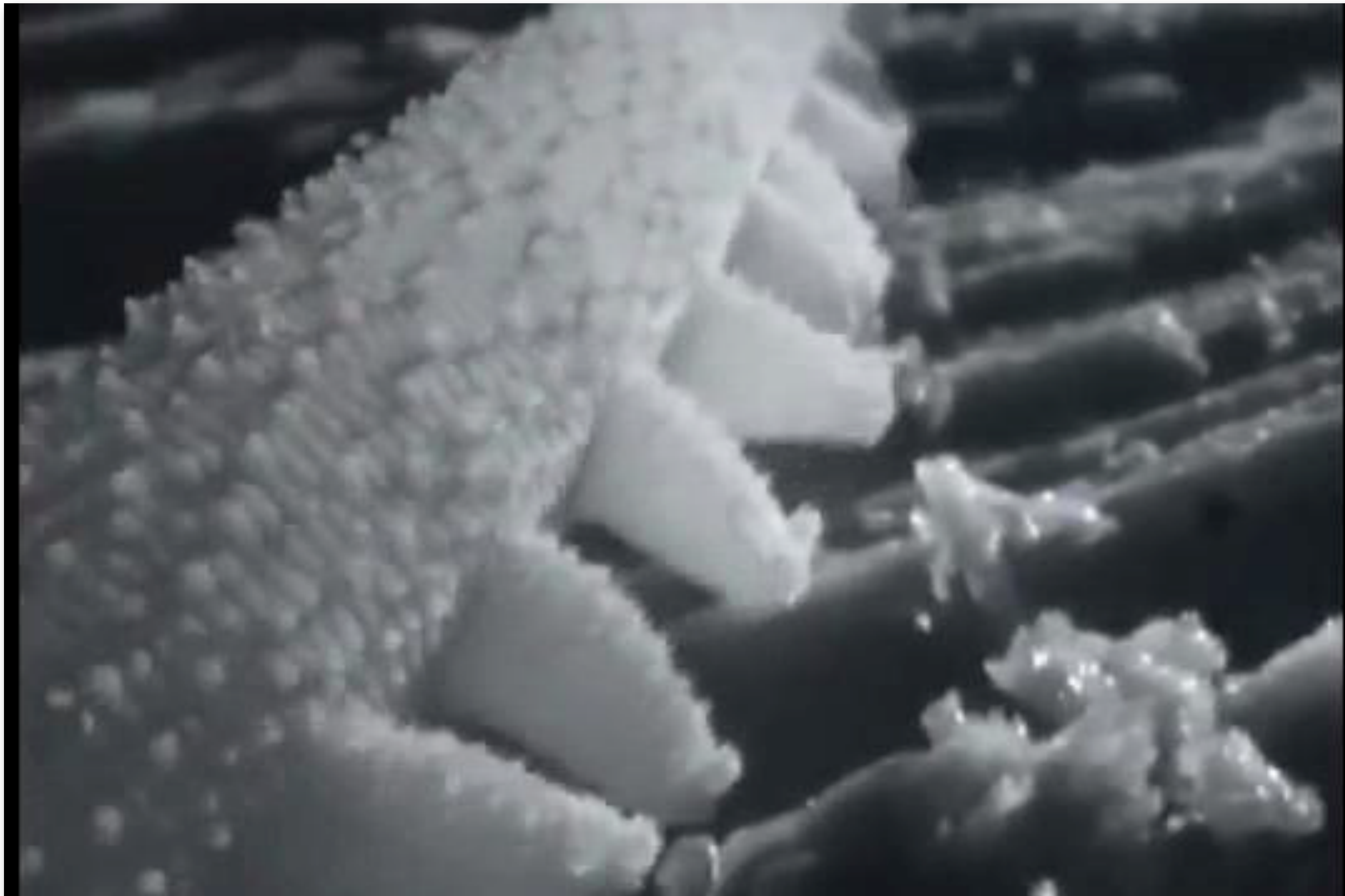
Velvet Worm 101

Onychophora: Greek *Onychos* for claws and *Phoros* for bearer



genus: Peripatus Solorzanoi

Actual attack...poor cricket



BBC Video Credit: Julian Monge-Najera

Average duration of a squirt $\Delta t \sim 0.064 \pm 0.005 \quad \text{s}$

This work

- Study of the fast oscillatory motion of the velvet worm oral papillae and the exiting liquid jet that oscillates with frequencies

$$f \sim 30 - 60 \quad \text{Hz}$$

- We show that the fast oscillatory motion is the result of a elasto-hydro-dynamic instability driven by:

The fast unsteady flow during squirting

The interplay between elasticity of oral papillae

Outline of the Talk

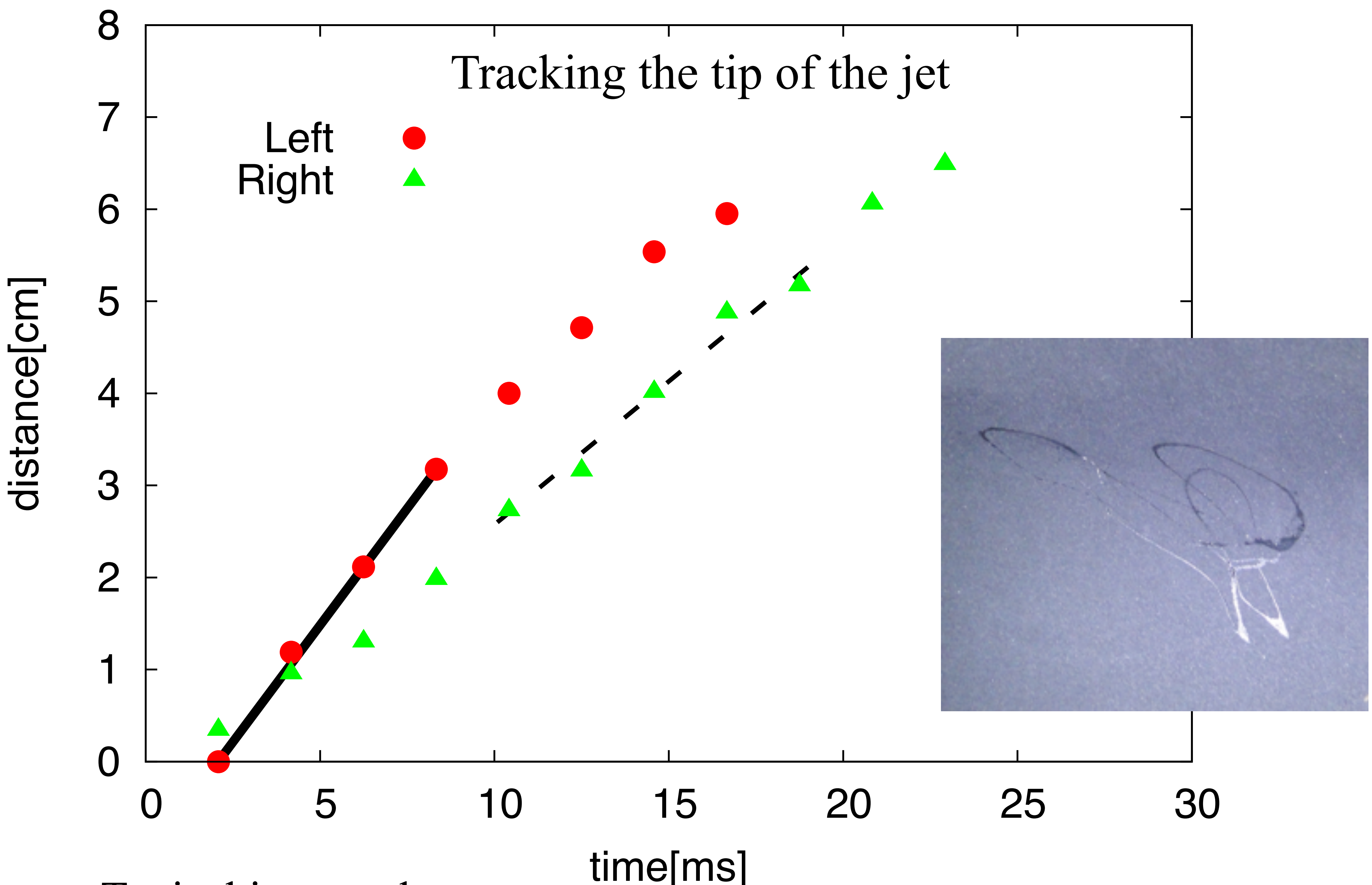
1. Worm attack kinematics
2. Anatomy of the ejecting system
3. Physical mechanism involved in squirting process
4. Synthetic simulacrum
5. Conclusions

1. Worm attack kinematics

High speed imaging to capture the attack in slow motion (240, 480)

Average duration of a squirt $\Delta t \sim 0.064 \pm 0.005 \quad \mathrm{s}$

1. Worm attack kinematics

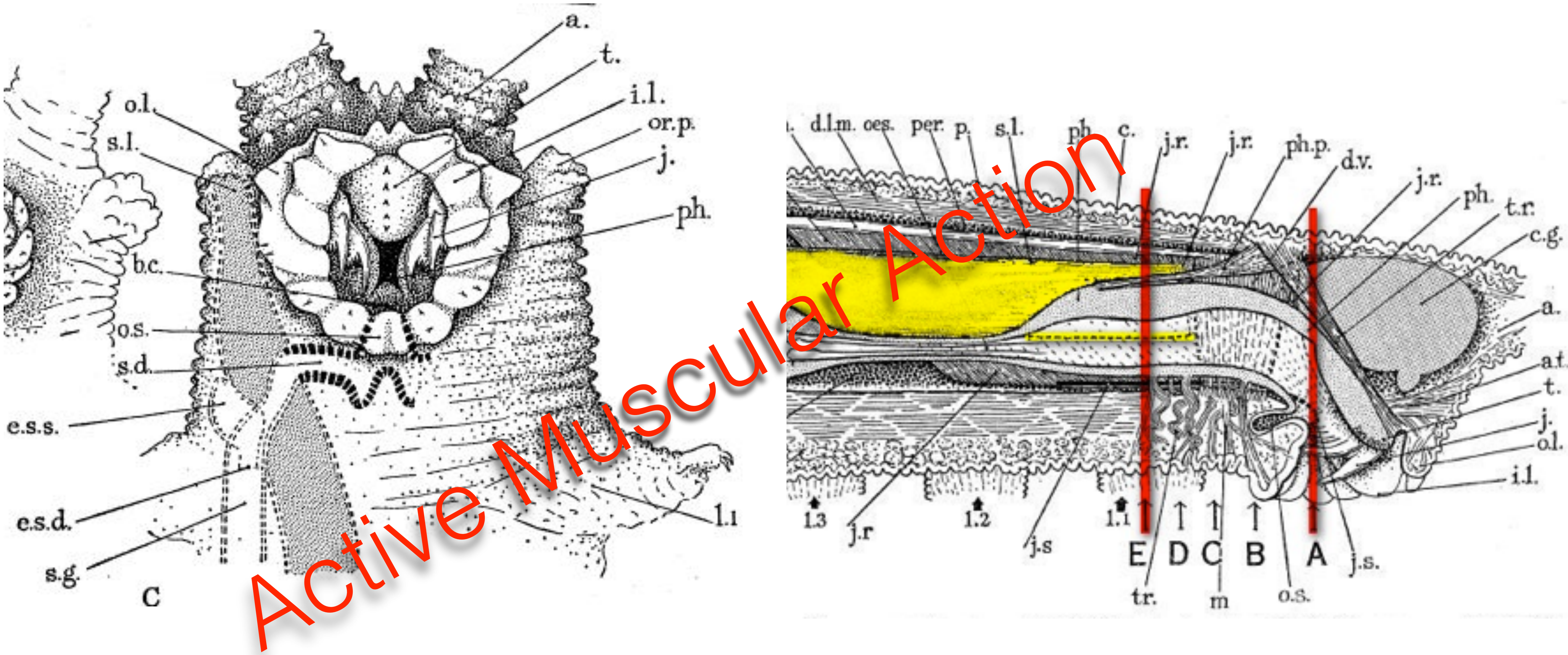


Typical jet speed

$$v \sim 3\text{–}5\ \mathrm{m\,s}^{-1}$$

$$f \sim 30 - 60 \quad \mathrm{Hz}$$

2. Anatomy of the ejecting system



Manton, S.M. 1937. Studies on the Onychophora. IV. Proceedings of the Royal Society of London, Part B 124: S41.

R.S.K. Barnes, Peter P. Calow, P.J.W. Olive, D.W. Golding, J.I. Spicer. 2001.
The Invertebrates: A Synthesis. 3rd ed.
Blackwell Science Ltd., Malden, MA, USA.

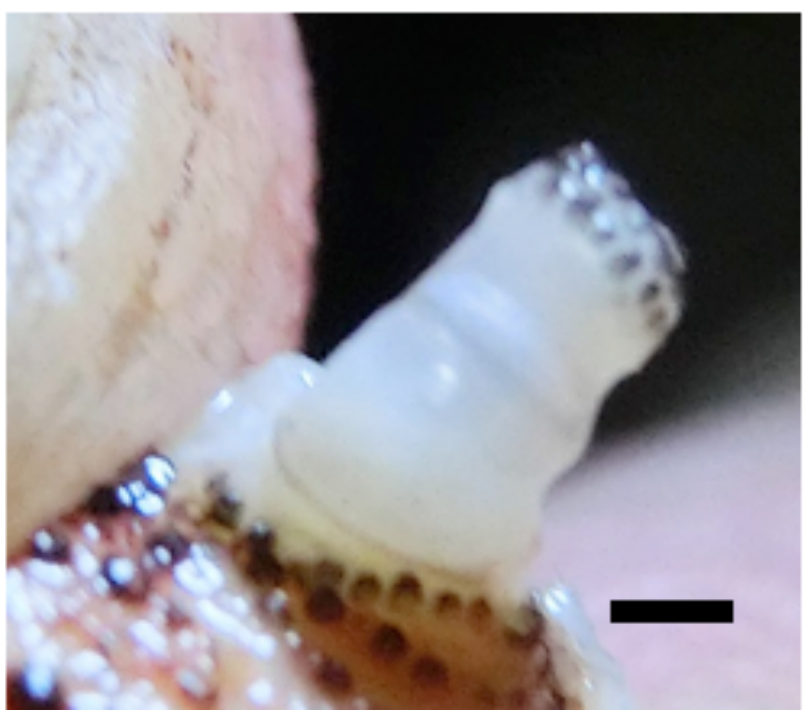
Previous theory: Active oscillations

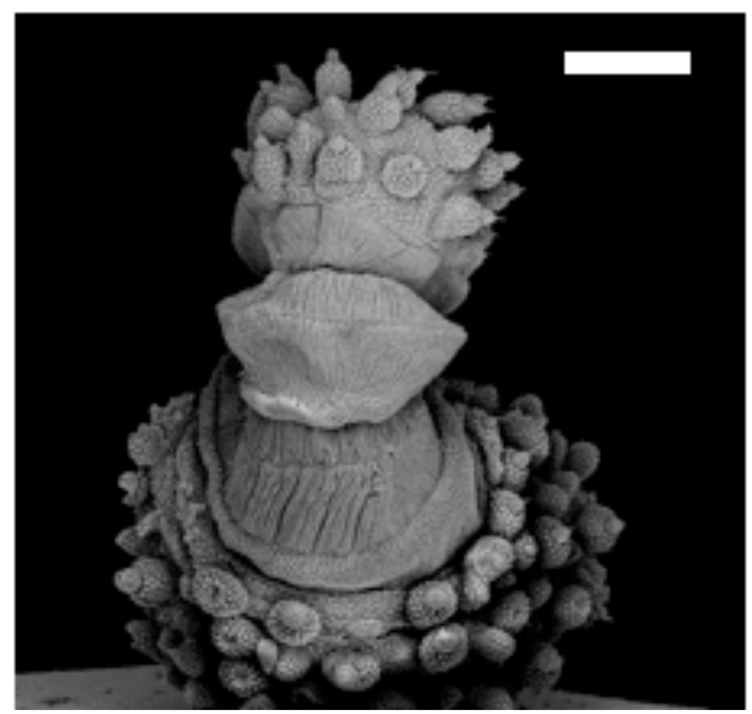
A new giant species of placented worm and the mechanism by which onychophorans weave their nets (Onychophora: Peripatidae)

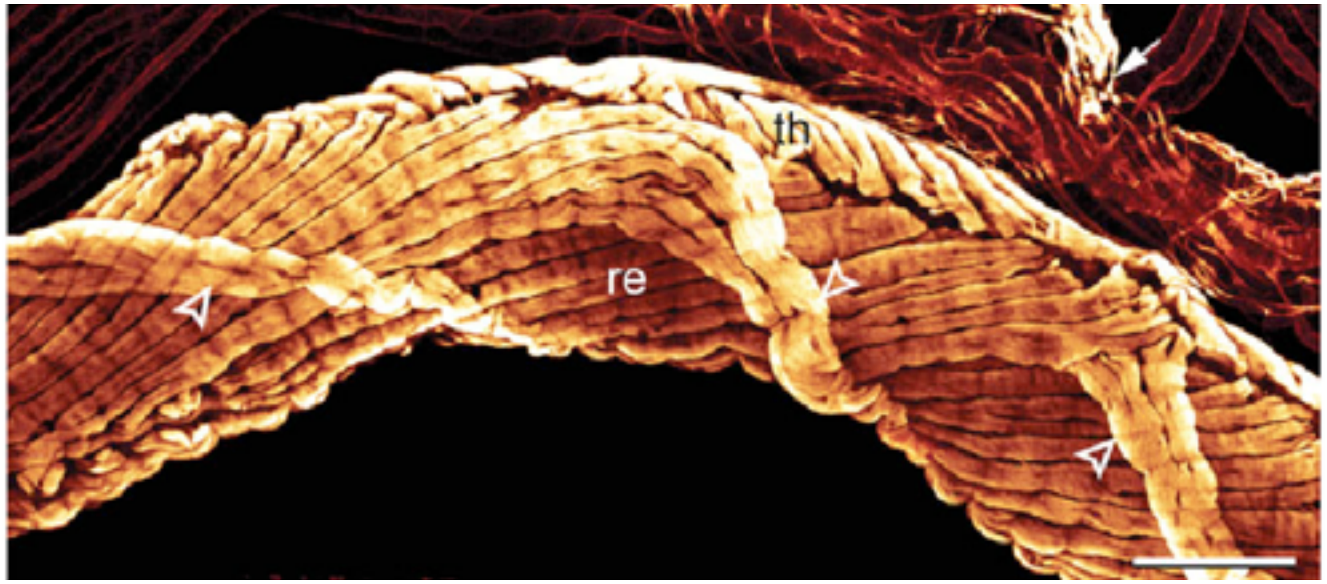
Rev. Biol. Trop. (Int. J. Trop. Biol. ISSN-0034-7744) Vol. 58 (4): 1127-1142, December 2010

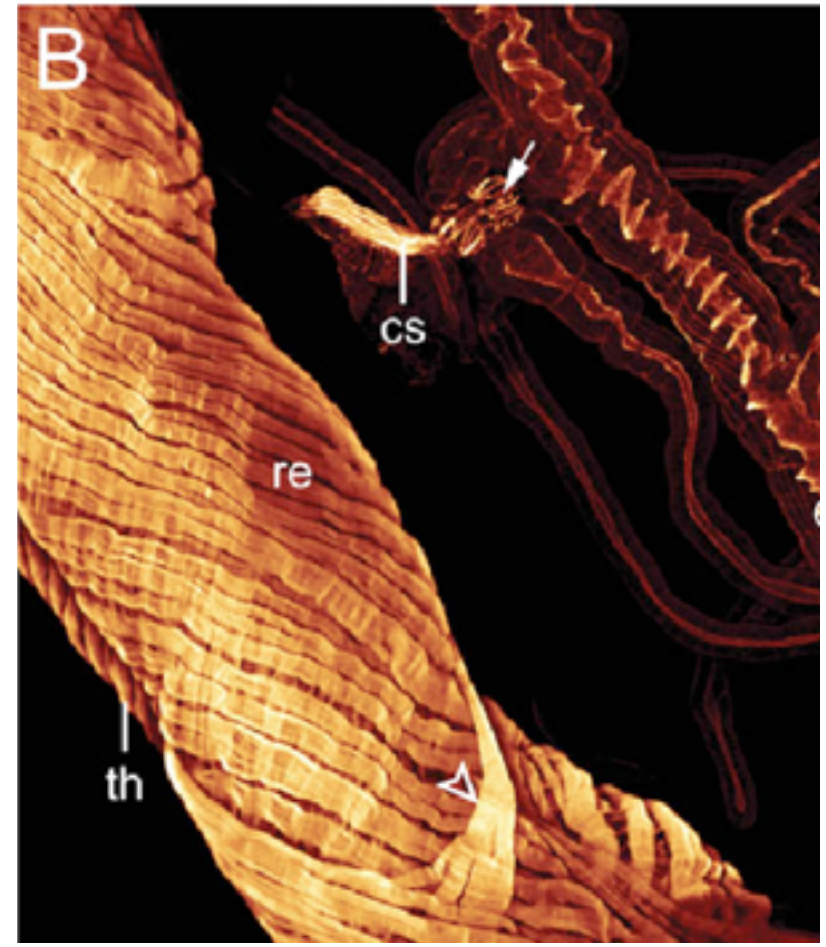
?

adhesive. Muscular action produces a swinging movement of the adhesive-spelling organs; as a result, the streams cross in mid air, weaving the net.









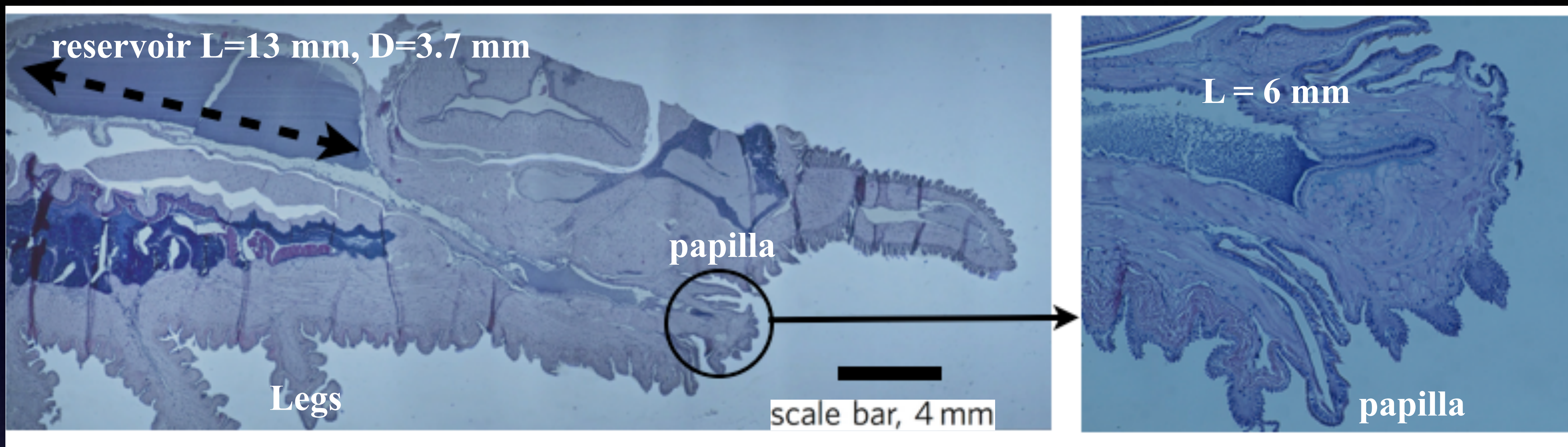
Reservoir muscular fibers

JOURNAL OF MORPHOLOGY 273:1079–1088 (2012)
Alexander Baer* and Georg Mayer

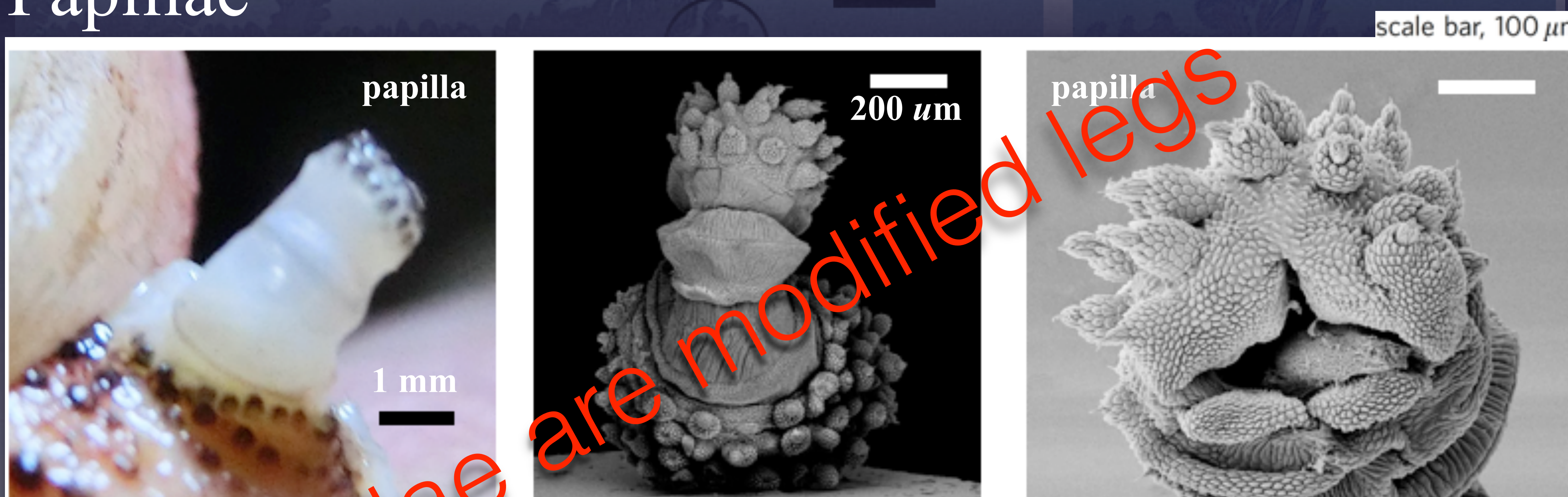
Fastest muscles in jaw. Twitch time: 0.5 s

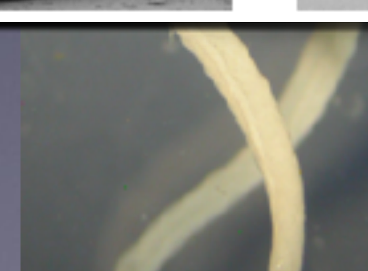
Papillary oscillations: 20 ms

New anatomical findings



Papillae





papillae are modified legs

Velvet worms are “slow”

Papillar oscillations are fast compared with any other motion of the worm

$$\frac{f_{\text{papila}}}{f_{\text{walking}}} \sim 30 - 60$$

Time scale for the fastest muscles in the worm

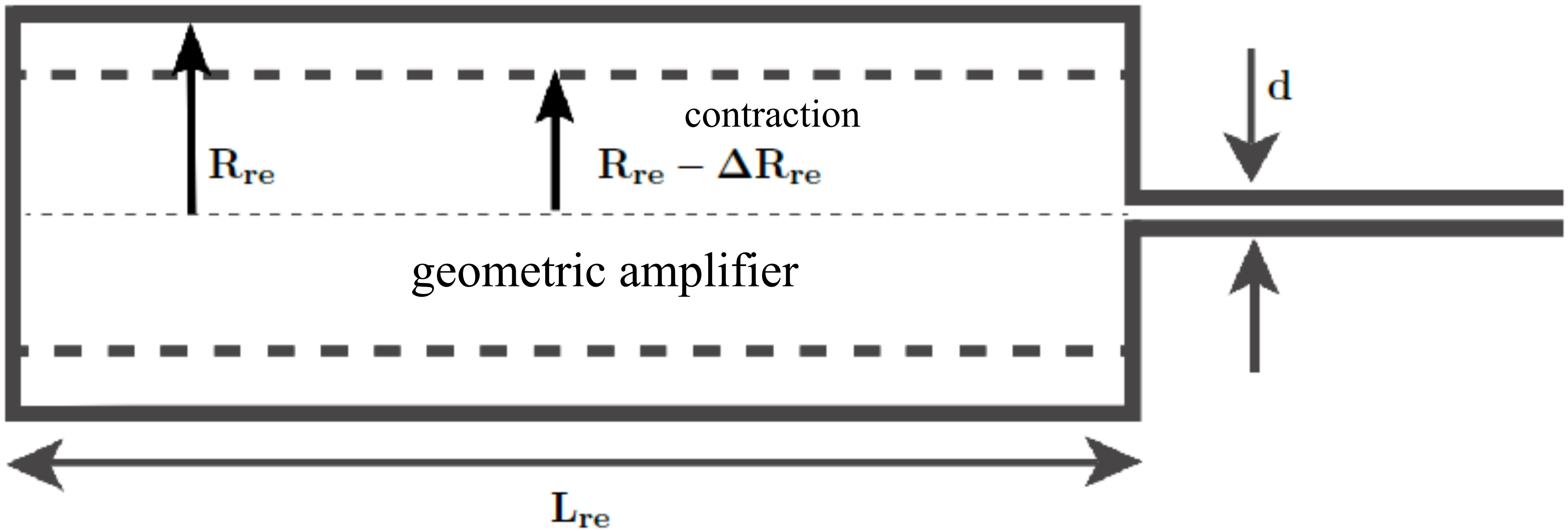
$$0.5 \quad s$$

But papilla oscillates fast!

Q: how the smile is accelerated?

3. Physical mechanism

$R_{re} \sim 2 \quad mm$



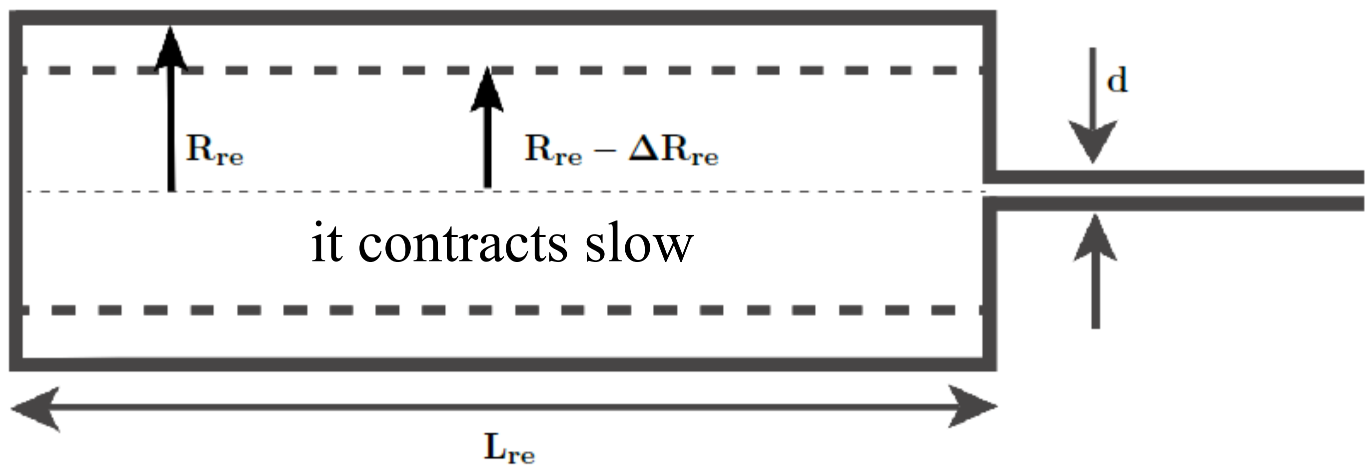
volume conservation

$$2\pi R_{re} \Delta R_{re} L_{re} = \pi \underbrace{r}_{\text{radius of slime}}{}^2 \mathcal{C} \} \text{ length of slime}$$

$\delta R_{re}/R_{re} < 0.03$ in about 0.12 sec! (by flow conservation)

enough to produce speeds of $V \sim 5 \quad \mathrm{ms}^{-1}$

Physical mechanism



Fluid inertia plays critical destabilizing role, if the ratio of inertial to viscous forces characterized by the Reynolds number

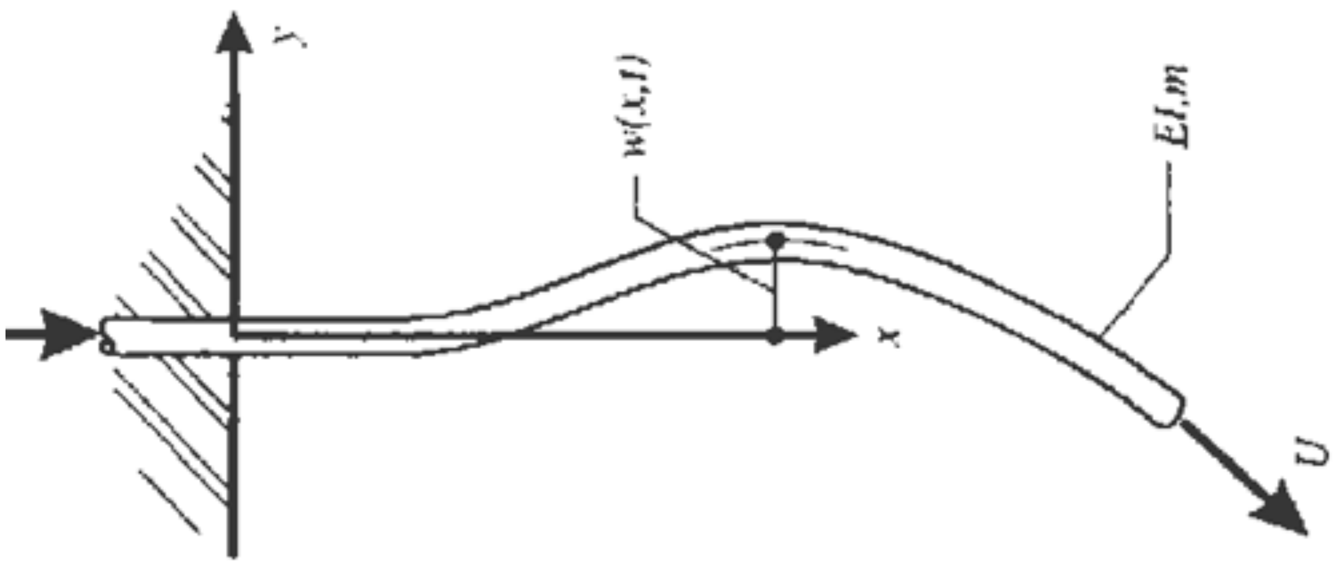
$$Re = VR/\nu > 1$$

In this case $Re \sim 2700$

This leads to the conclusion that the instability arises due to a competition between fluid inertia and elastic resistance.

Physical mechanism

Garden hose pipe



"Handshower Experiment"

Dimensionless equation of motion

Bending Stiffness

M: mass density per unit length of the fluid in the pipe

$$\frac{\overbrace{EI}}{\lambda^4} \sim \frac{Mvf}{\lambda} \sim \frac{Mv^2}{\lambda^2}$$

Elastic — Coriolis — Centrifugal

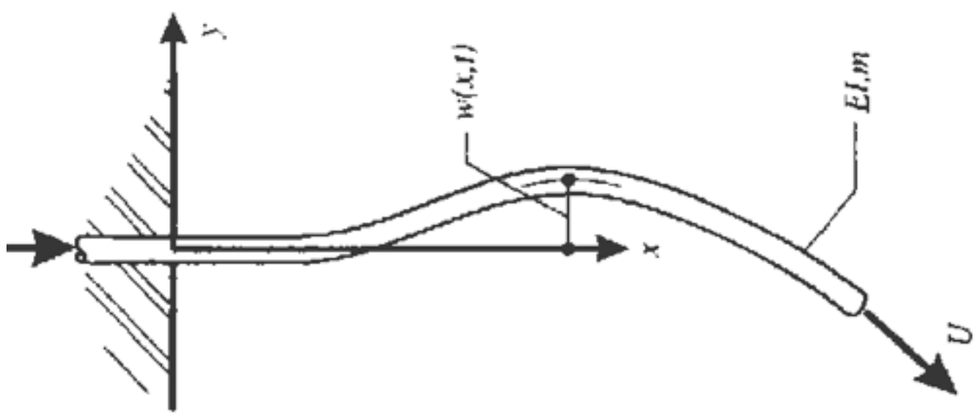
$\lambda \sim 2L$

oscillation wavelength

MEASURED $f \sim \left(\frac{EI}{M}\right)^{1/2} \frac{1}{4L^2}$

BALANCE CORIOLIS V/S ELASTIC FORCES

Physical mechanism



$$\frac{EI}{\lambda^4} \sim \frac{Mvf}{\lambda} \sim \frac{Mv^2}{\lambda^2}$$

$$u_0 \sim f\lambda = \left(\frac{EI}{M}\right)^{1/2} \frac{1}{L}$$

$L = 6.0 \;\; \text{mm} \qquad f \sim 58 \;\; \text{Hz} \qquad E = 20 \quad kPa$

$$v_c \sim 2\pi u_0 = 3 \quad \text{ms}^{-1}$$

At this critical speed, stability is lost via a Hopf type bifurcation

Physical Model

$$\overbrace{EIz^{(4)}}^{\text{bending}} + \left\{\underbrace{MV^2}_{\text{centrifugal}} + \left[\overbrace{M\frac{dV}{dt}}^{\text{unsteadiness}} - \overbrace{(M+m)\,g}^{\text{gravity}}\right](L-x)\right\} z^{(2)} + \overbrace{2MV\frac{\partial^2 z}{\partial x \partial t}}^{\text{coriolis}} +$$

$$\underbrace{(M+m)\,g\frac{\partial z}{\partial x}}_{\text{gravity}} + \underbrace{\nu\frac{\partial z}{\partial t}}_{\text{damping}} + \underbrace{(M+m)\frac{\partial^2 z}{\partial t^2}}_{\text{inertia}} = 0$$

z : oscillation amplitude, ν : phenomenological damping

Boundary conditions

$$z(0,t) = 0 \quad z^{(1)}(0,t) = 0 \quad z^{(2)}(L,t) = 0 \quad z^{(3)}(L,t) = 0$$

Dimensionless Equation

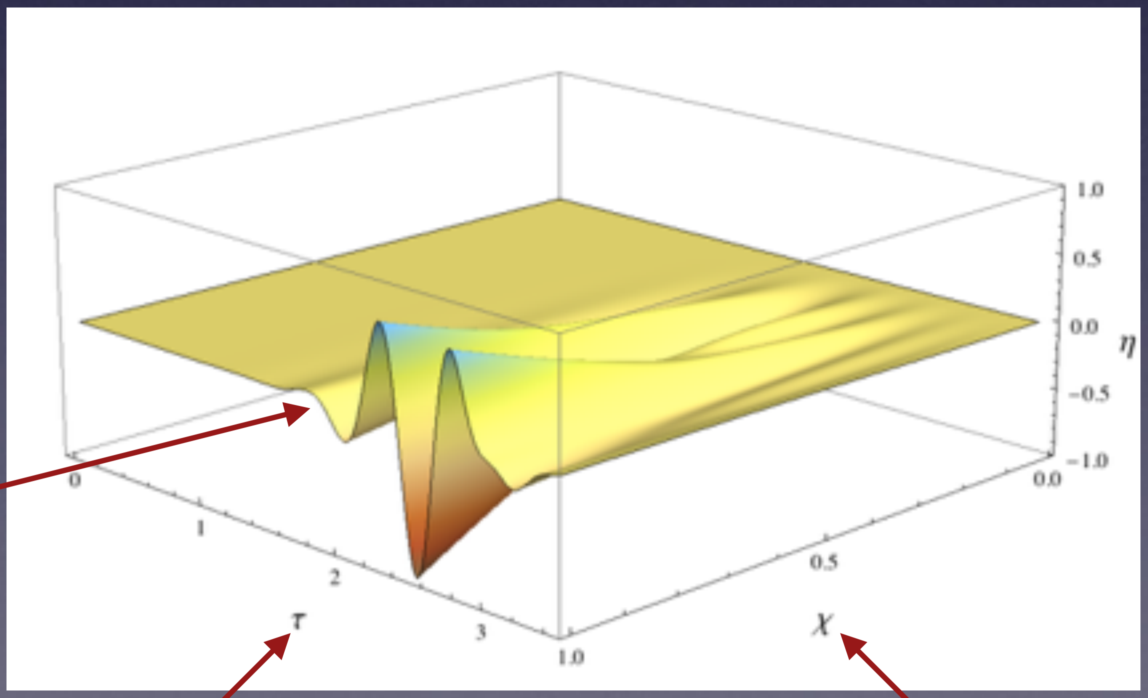
dimensionless time
and coordinates

$$\frac{\partial\eta^4}{\partial\chi^4} + \{u^2 + \left(\beta^{1/2}\dot{u}(\tau) - \gamma\right)(1-\chi)\}\frac{\partial\eta^2}{\partial\chi^2} +$$
$$2\beta^{1/2}u(\tau)\frac{\partial^2\eta}{\partial\tau\partial\chi} + \gamma\frac{\partial\eta}{\partial\chi} + \sigma\frac{\partial\eta}{\partial\tau} + \frac{\partial^2\eta}{\partial\tau^2} = 0$$

$\eta = z/L \qquad \chi = x/L \qquad u = V/u_0 \qquad \tau = t/\tau_0$

τ_0 : bending time scale

Captures well the onset of the instability.



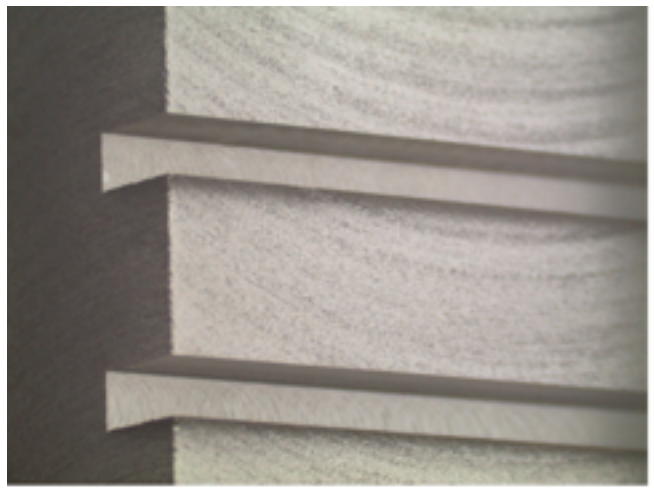
4. Synthetic simulacrum

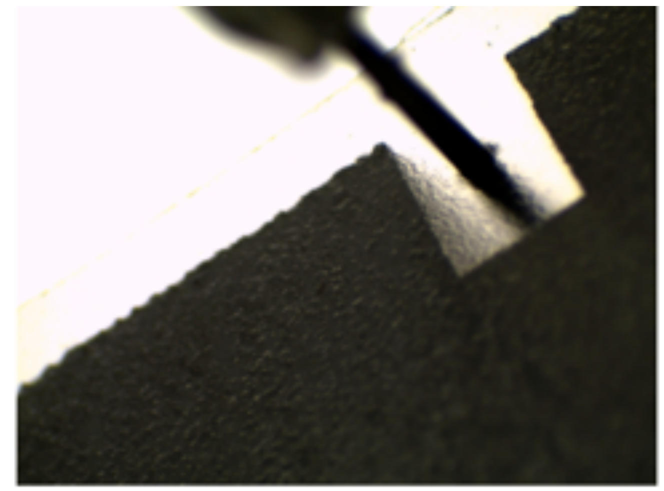
Micro-milling channels

Insulin Syringe

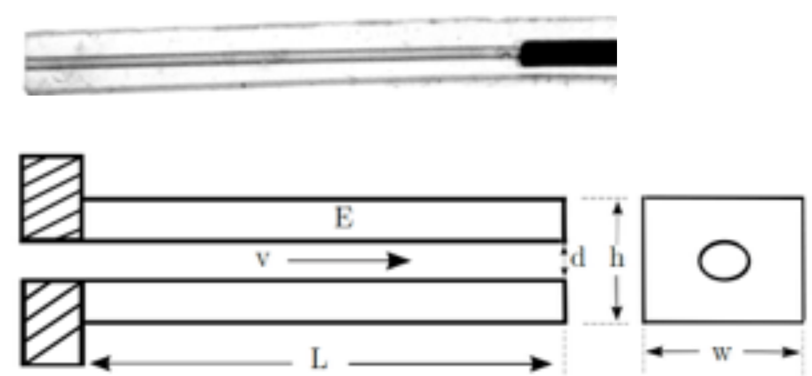
Scotch tape

PDMS





Synthetic papilla

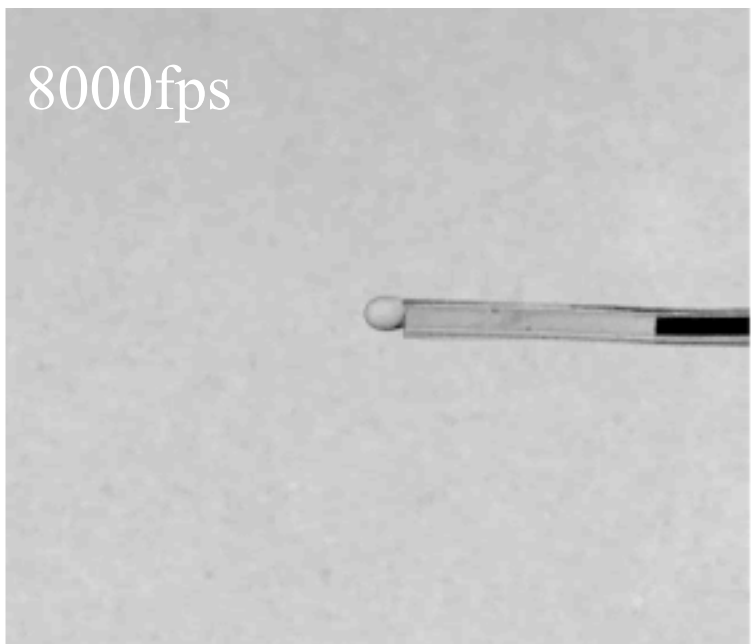


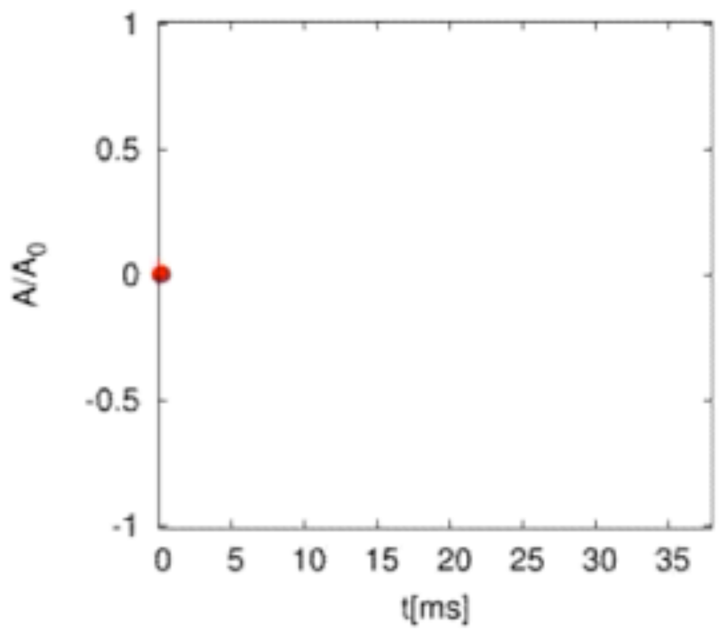
d = 0.81 mm w = 1.60 mm L = 9.5 mm E = 288 kPa h = 1.42 mm

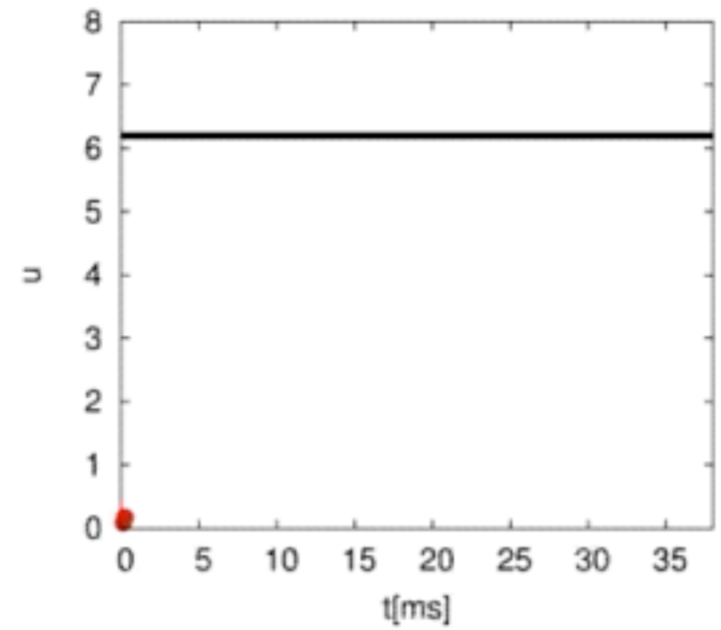
There is no roughness along the inner part of the duct, or an external accordion like geometry

Synthetic simulacrum

Synthetic papilla becomes unstable and oscillates when the liquid reaches a speed $V_c = 8.6$ m/s

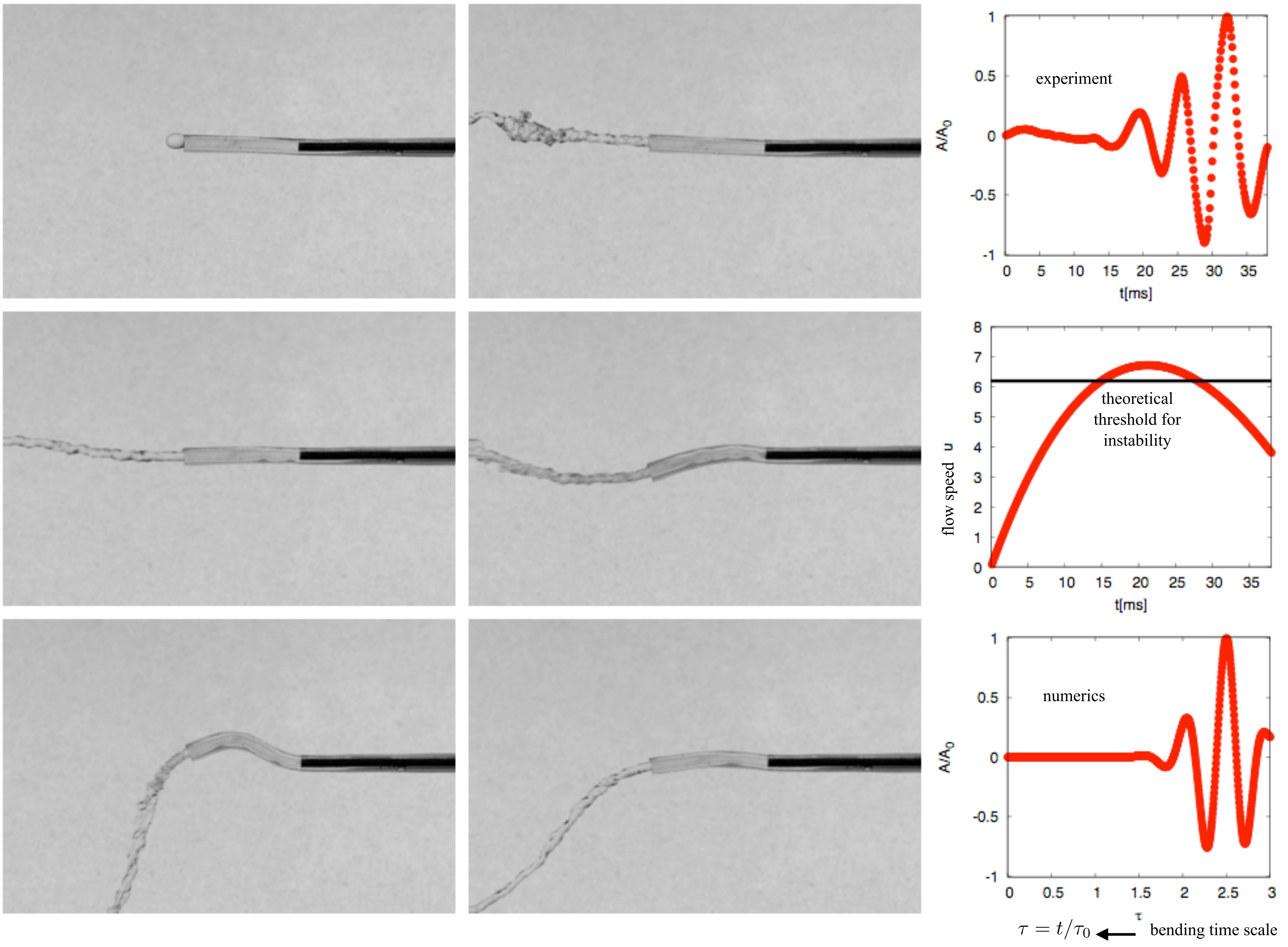






This occurs in the same range of dimensionless parameters that for the natural organ in agreement with theoretical predictions

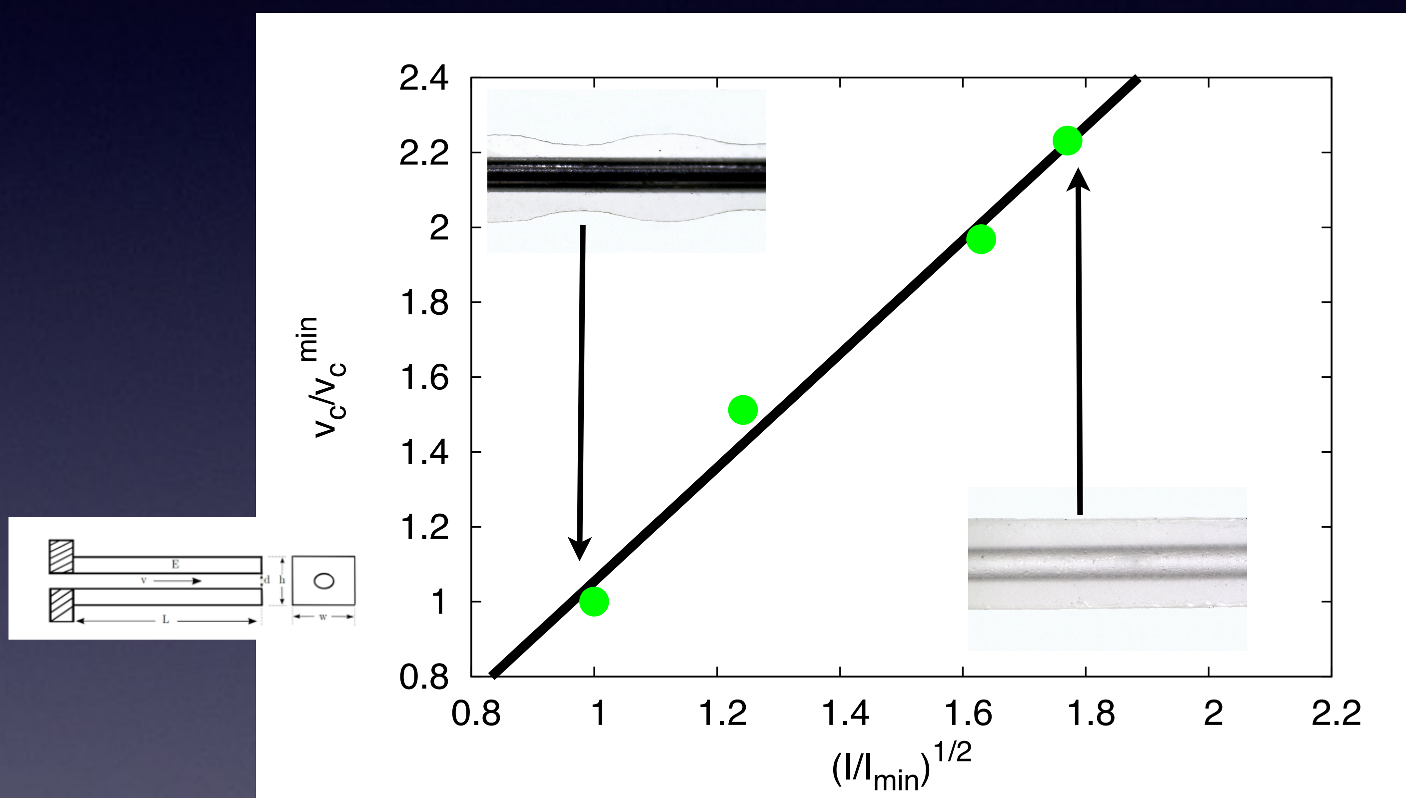
Fast muscular action at the papillary level is unnecessary for oscillations



experiment
A/A0
t[ms]
flow speed u
theoretical threshold for instability
t[ms]
numerics
A/A0
τ
τ = t/τ0
bending time scale

V_c lowers as the amplitude of external roughness increases

B = EI can locally change up to 1/10 of the stiffness of a papilla



$$V_c \sim I^{1/2}$$

Microtubes with accordion like shapes varying the degree of external roughness (their width w).

V_c lowers as we increase the amplitude of external roughness

The effect of inner pipe imperfections is to decrease the effective cross section of the tube, as well as to anticipate the transition to turbulence.

5. Take home message

- Velvet worms can spray a web rapidly to entangle their prey without resorting to a complex neuromuscular control strategy

- They harness the instability associated with rapid flow through a long soft nozzle that causes it and the exiting jet to oscillate

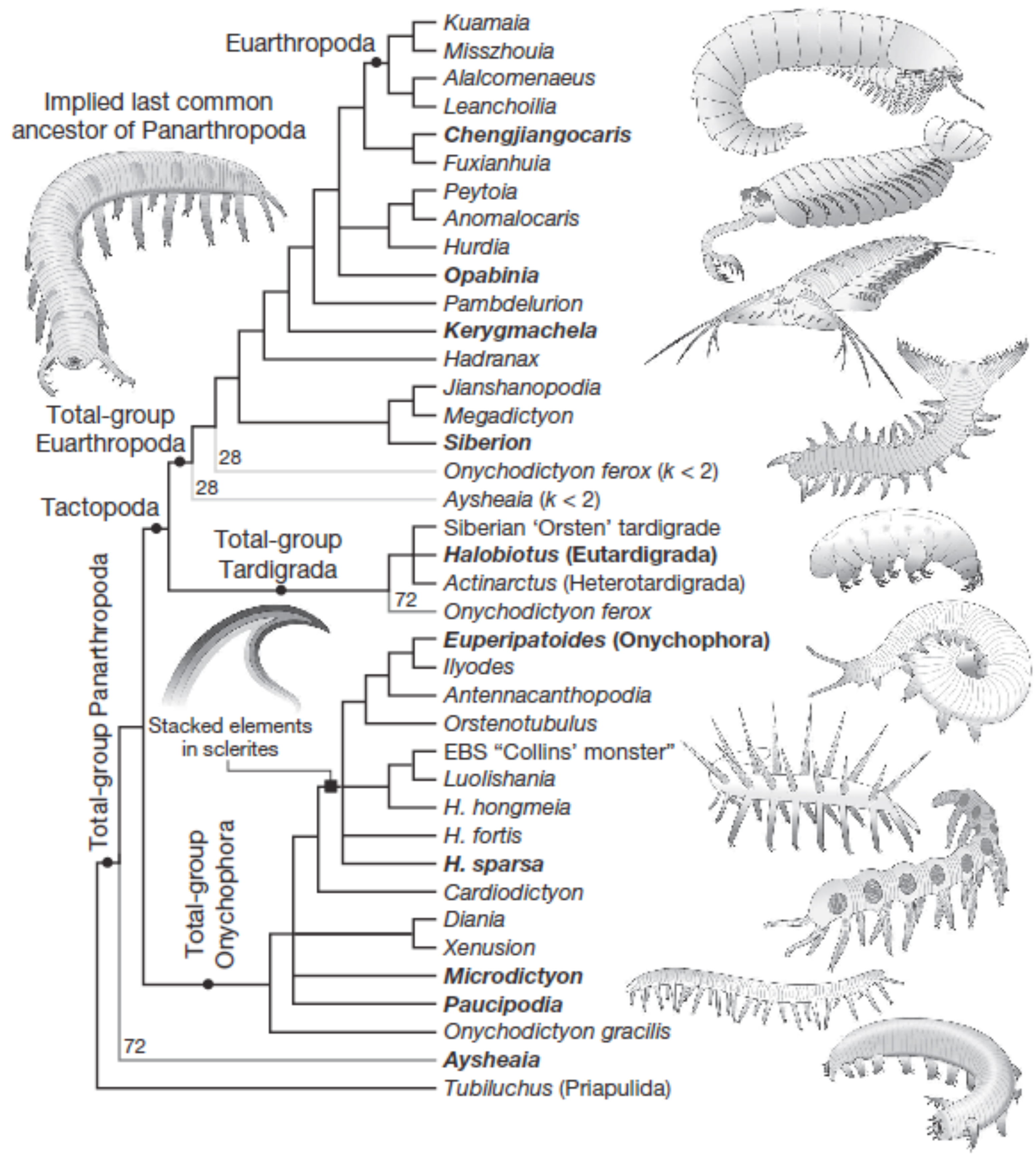
- Passive strategies can be cleverly harnessed by organisms, which inspires:

- Microfluidic devices
- Micro and nanofiber production

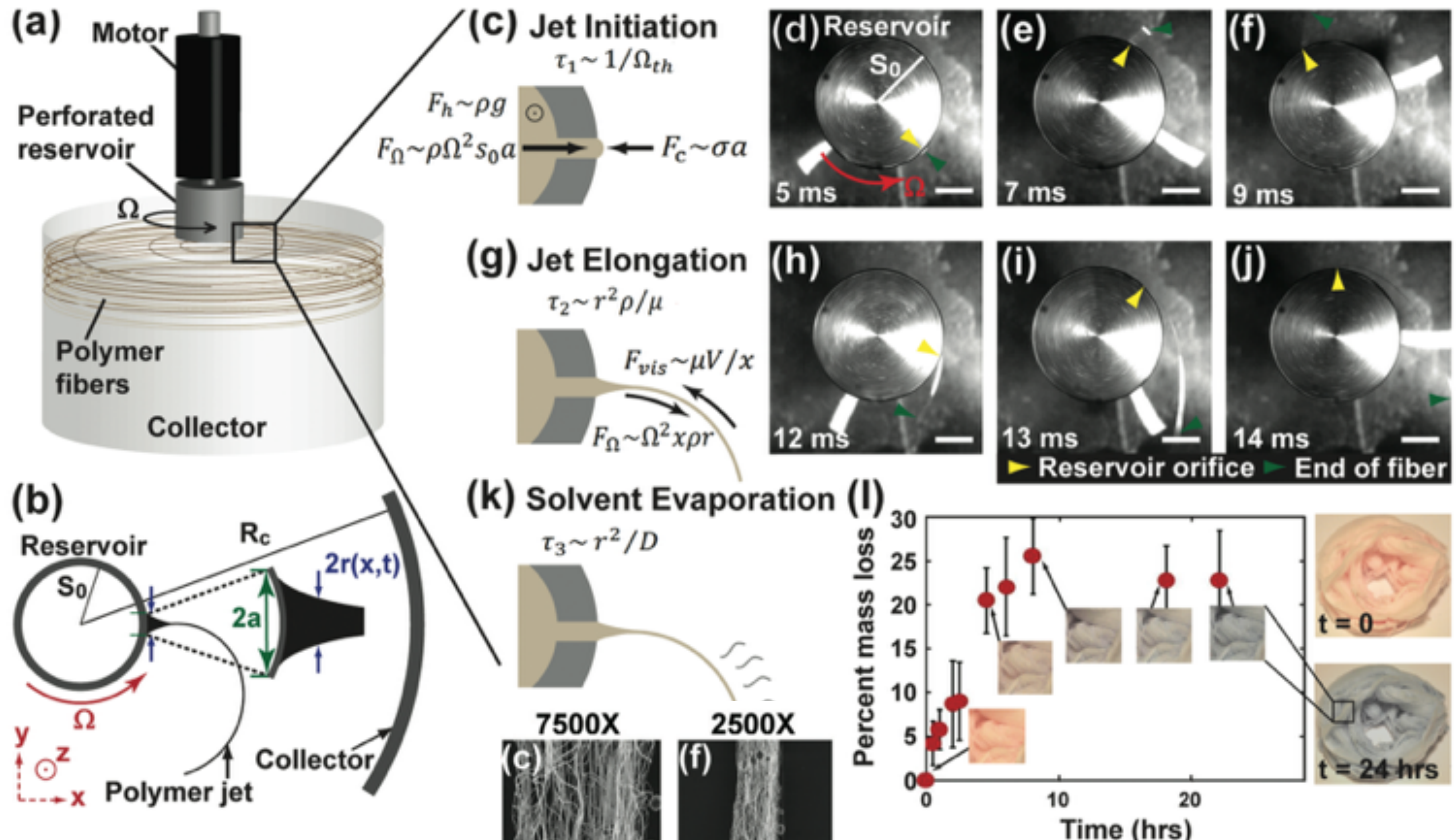
more details at

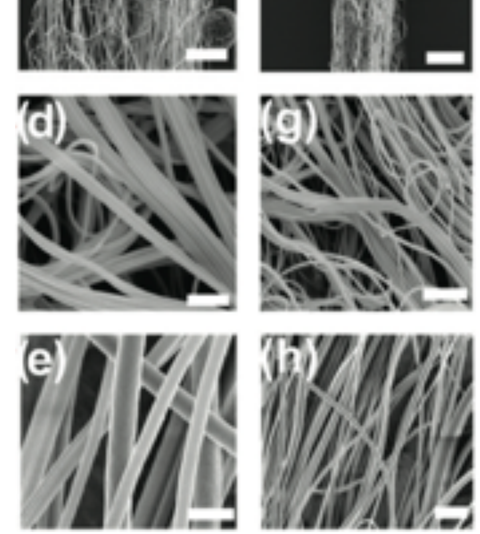
NATURE COMMUNICATIONS | DOI: 10.1038/ncomms7292

Evolutive importance of velvet worms



Rotary jet spinning





Mellado *et. al.* Appl. Phys. Lett. 99, 203107 (2011)