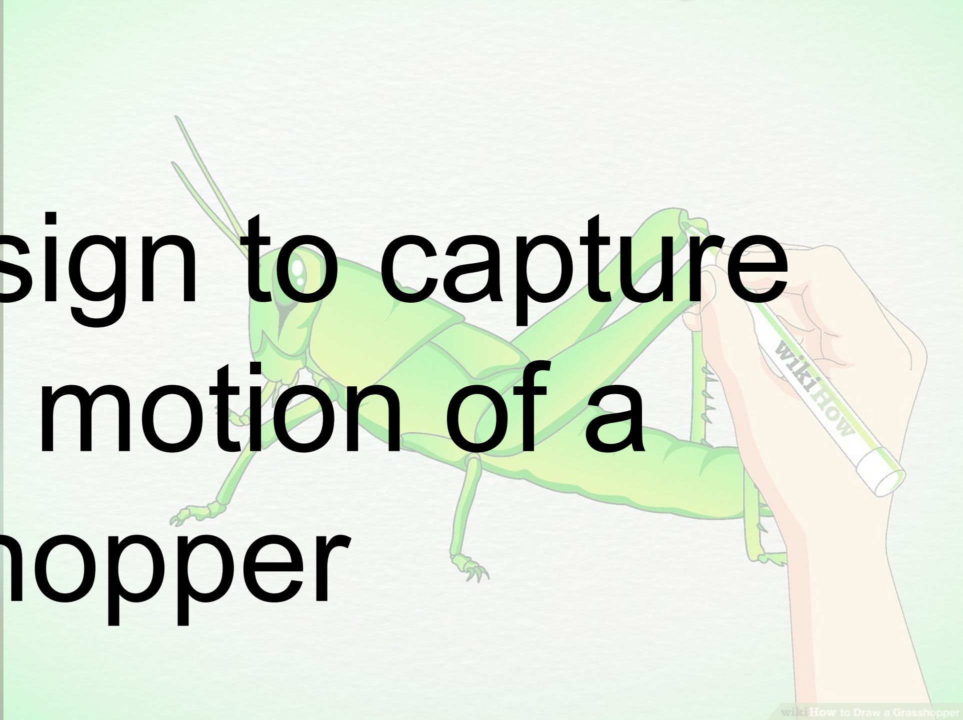


Soft Robot design to capture the jumping motion of a grasshopper

Trudy Adjei & Andrew Thompson

Grasshopper fun fact

- Grasshoppers can jump about 25cm high and 1m long
    - Humans could leap more than the length of a football field

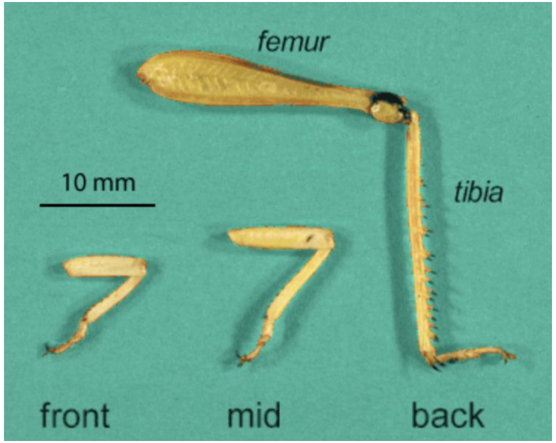
Heitler, 1974
Heitler’s grasshopper website

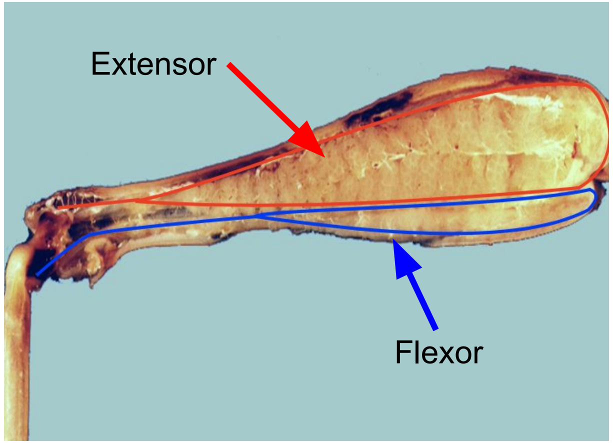
The jumping mechanism - ‘Catapult mechanism’

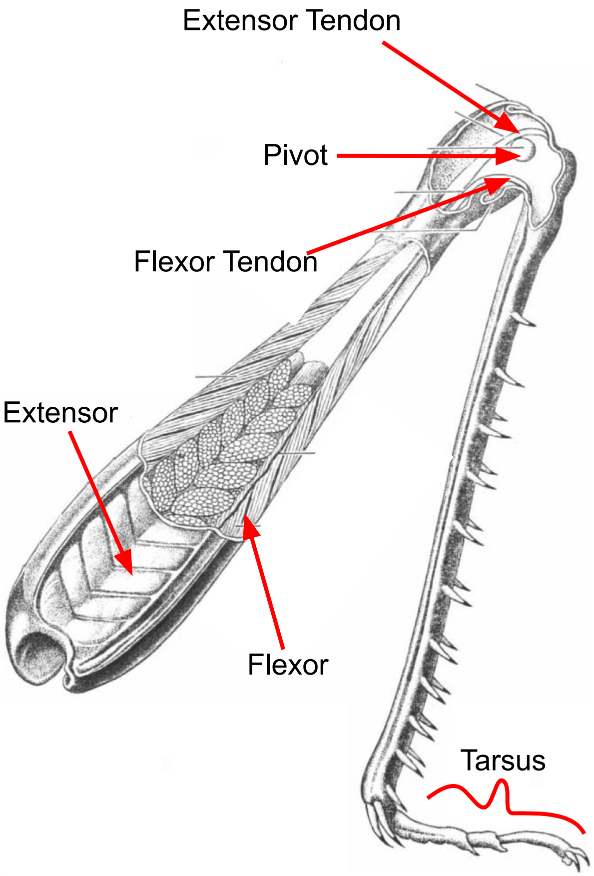
Muscle contracts - force generation → Bow is drawn back slowly → Energy is stored in bending bow → Release bow - energy is transferred to arrow

So how does the grasshopper do it?

- Hind limbs are the longest and largest
- Extensor muscle is very large for large force generation
- The extensors develop about 14N force



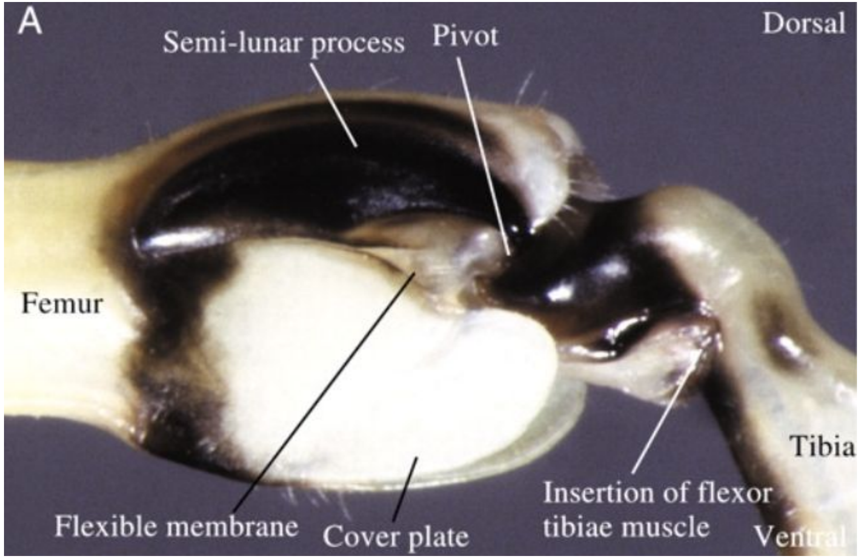


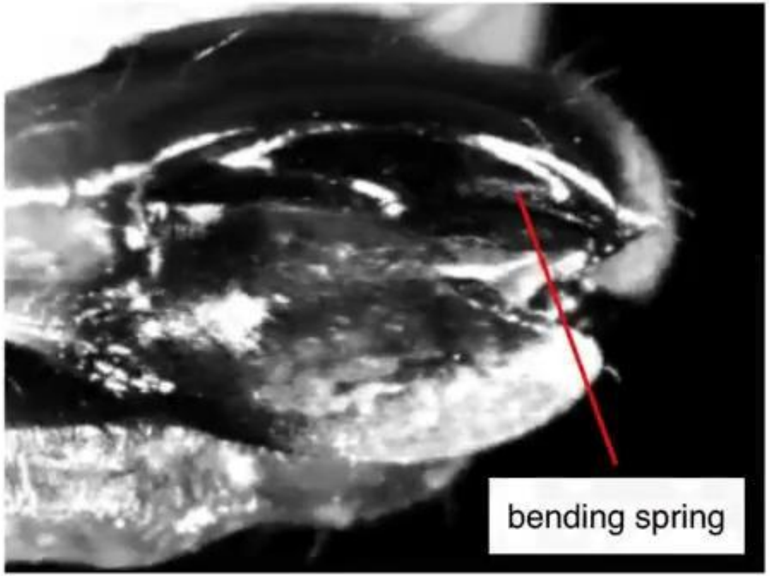


Heitler, 1977; Hoyle, 1958

So how does the grasshopper do it?

- It has its own spring → semi-lunar process
- Bending of the spring leads to energy storage
- Similar to the catapult mechanism

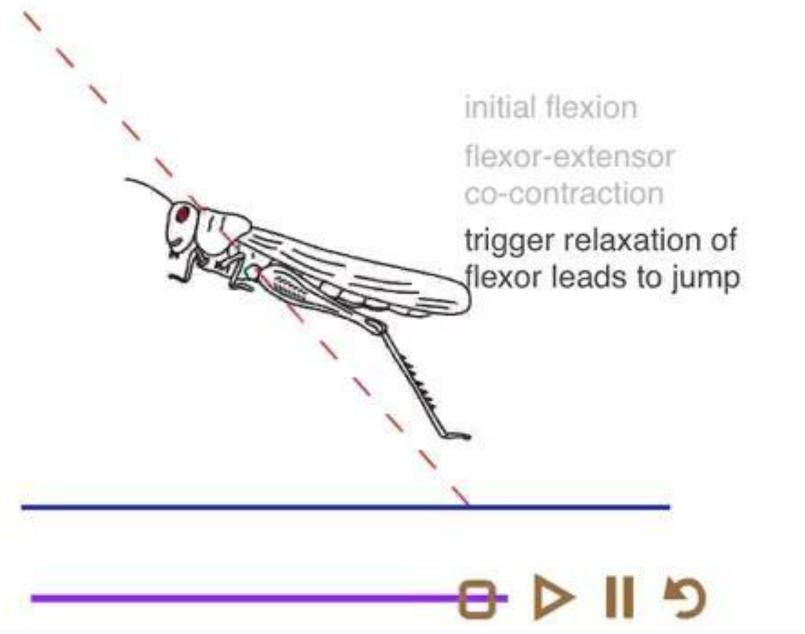




Heitler and Burrows, 1977
Burrows and Morris, 2001

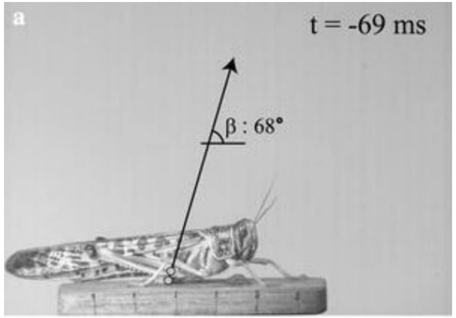
The jumping mechanism - the stages of jump

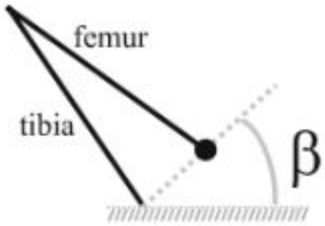
- Cocking stage: Hind legs are fully flexed by contraction of flexor muscle
- Co-contraction stage: Both flexors and extensors contract simultaneously
- Triggering stage: Relaxation of flexor muscles trigger rapid leg extension



Heitler and Burrows, 1977
Heitler's grasshopper website

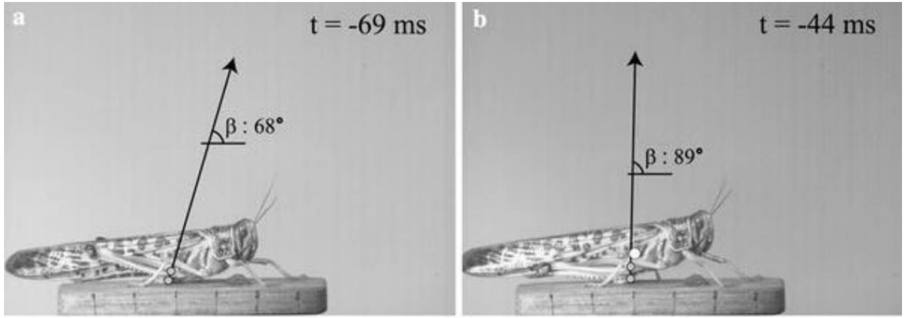
How do they control the jump?





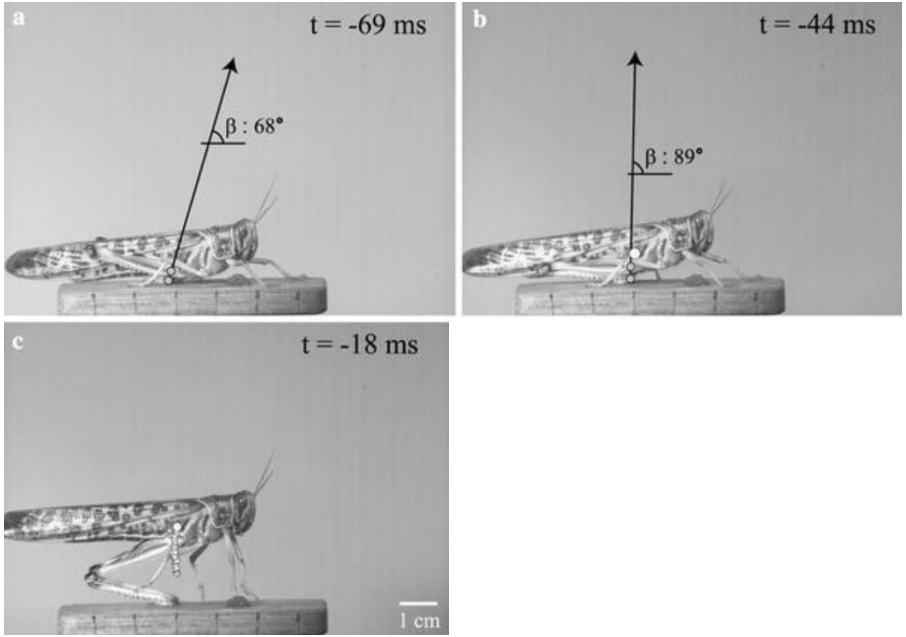
Sutton and Burrows, 2008

How do they control the jump?



Sutton and Burrows, 2008

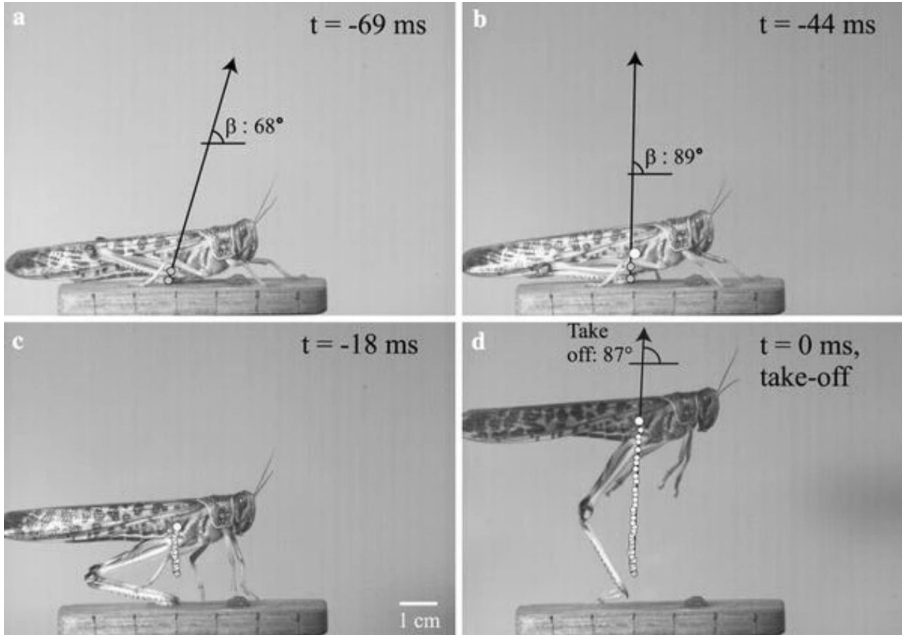
How do they control the jump?

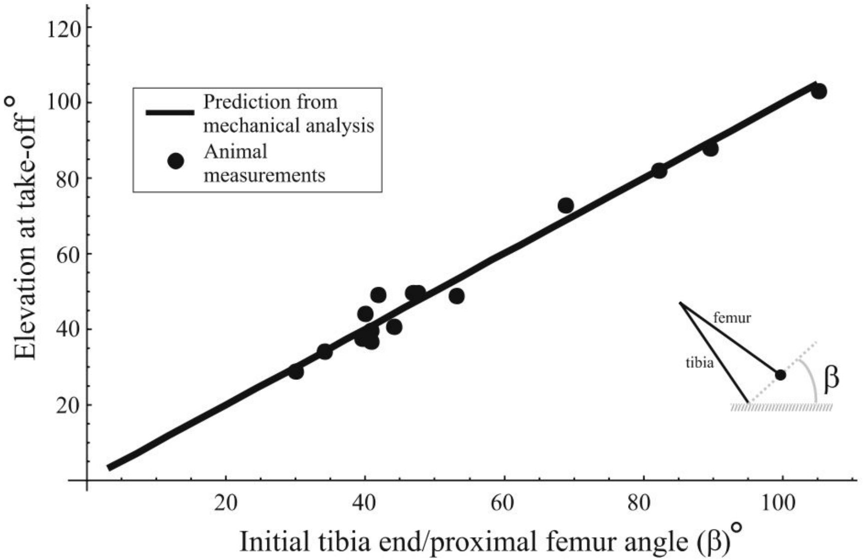


Sutton and Burrows, 2008

How do they control the jump?

- Angle of elevation is controlled by orientation of the hind legs relative to the body



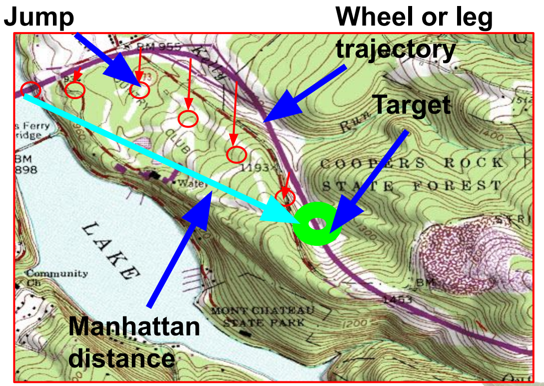


- Elevation is controlled by azimuth and speed
  - Azimuth is controlled by fore and middle legs
  - Speed, by the rate of energy release in the muscles

Sutton and Burrows, 2008

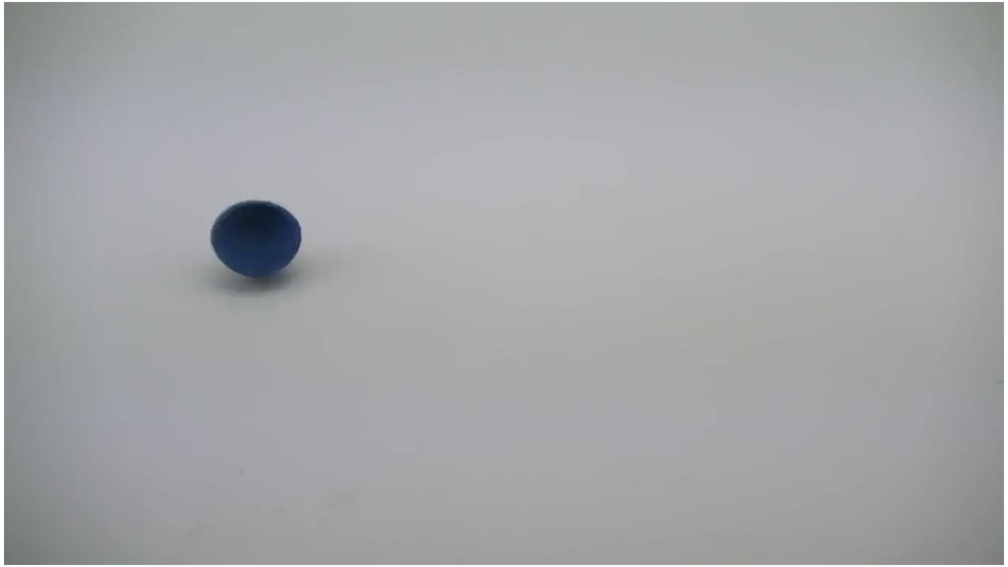
Why is this important?

- Move in complex environments and overcome obstacles
- Help in search and rescue
- Be useful for interplanetary exploration
- Addition of vertical axis increases effective motion planning



Isochoric Snapping Actuators

- Same mechanism in jumping popper toys



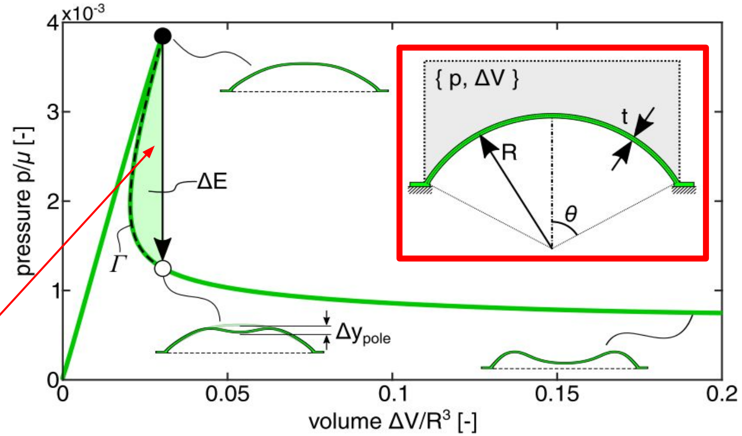
Gomez et al, 2018

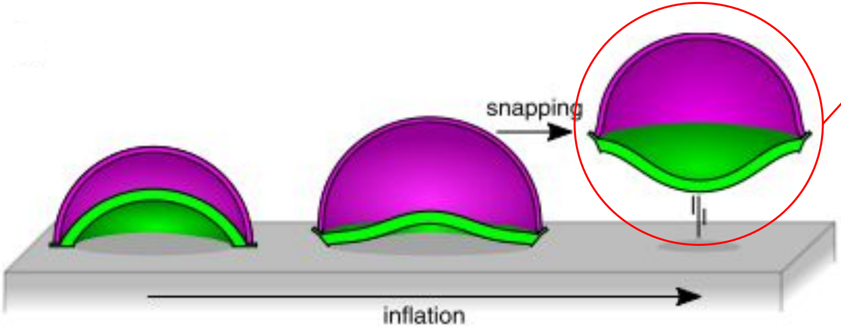
Video adapted from SonicDadDotCom

Isochoric Snapping Actuators

- Fluidic soft actuators exhibit isochoric instability when pressurized under volume controlled conditions

- This instability leads to sudden energy release and actuator displacement

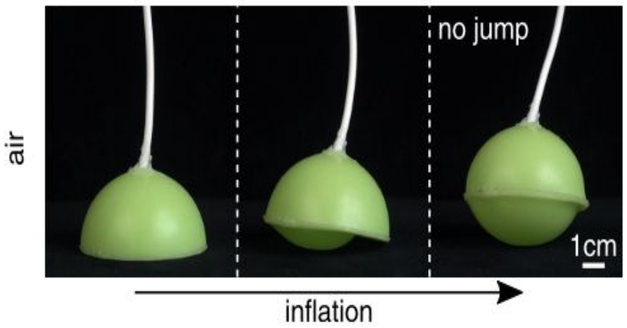




$$\Delta E = \int_{\Gamma} p \, d\Delta V,$$

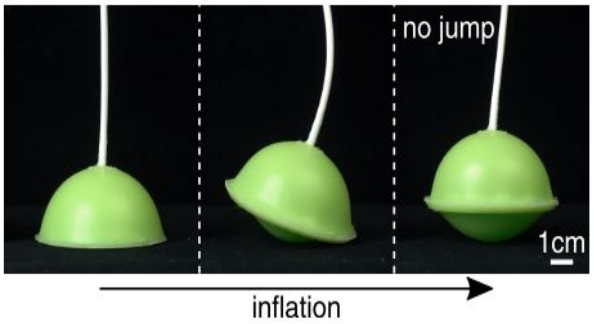
Isochoric Snapping Actuators

- The geometry and the type of material are crucial for controlling isochoric snapping



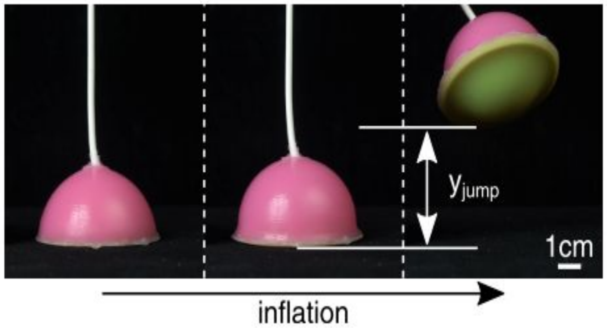
A

Polar angle: 60 degree
Normalized radius: 30



B

Polar angle: 60 degree
Normalized radius: 8.5



C

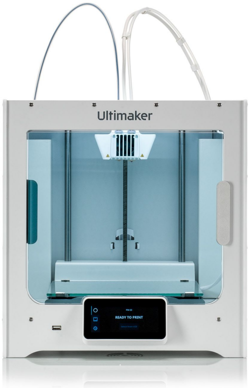
Polar angle: 60 degree
Normalized radius: 8.5
Softer rubber outer cap

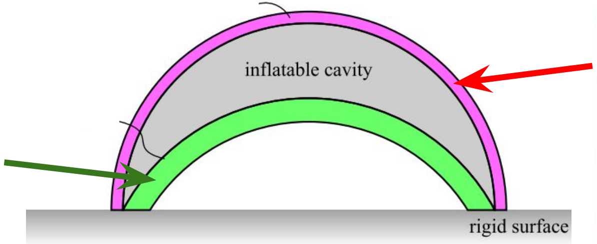
Comparison between isochoric snapping mechanism and grasshopper jumping

Isochoric Snapping	Grasshopper Jumping
Elastic energy is stored during inflation	Elastic energy is stored during co-contraction
Sudden release of elastic energy post inflation	Sudden release of elastic energy post flexion
Greater energy -> Larger displacement	Greater force -> Greater energy -> the higher the jump
Geometry and material affects energy released	Force affects energy released
Can be executed with soft materials like rubber	Is executed by muscles on exoskeletons

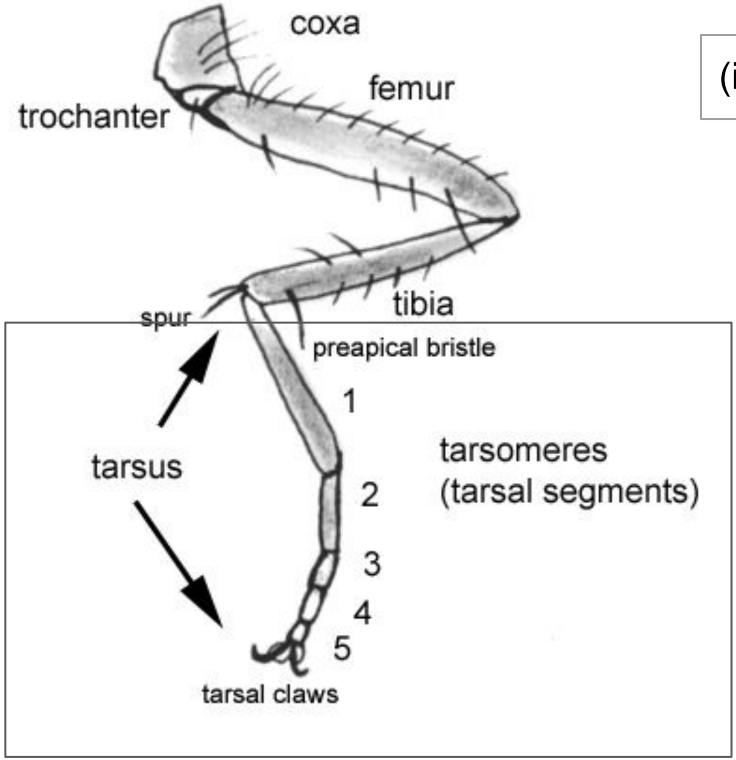
Materials & Fabrication (not including electronics)

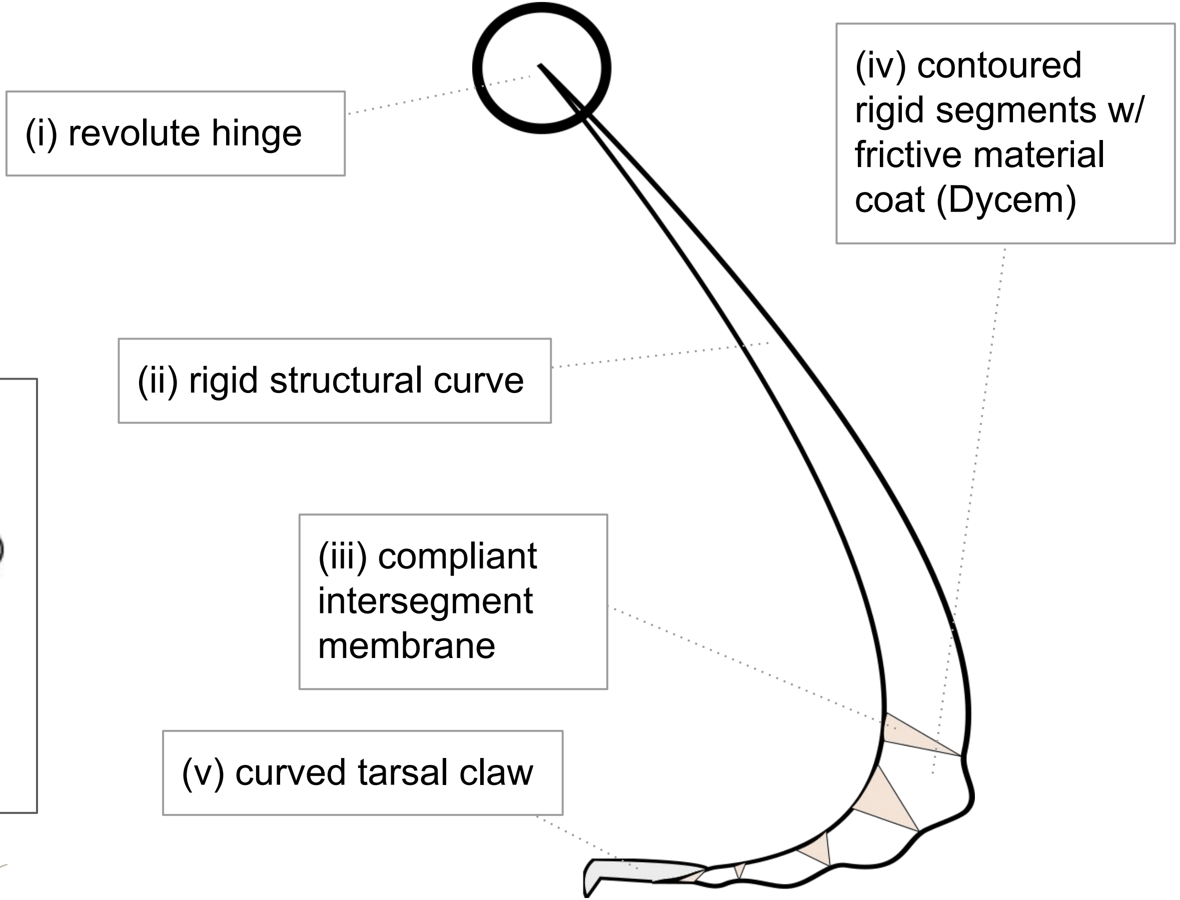
- Soft materials:
  - Zhermack Elite Double X
  - Dycem Non-Slip
- Rigid materials:
  - Fiberlogy IMPACT PLA
- 3D Printer (FDM)
  - e.g., Ultimaker, Stratasys, etc.





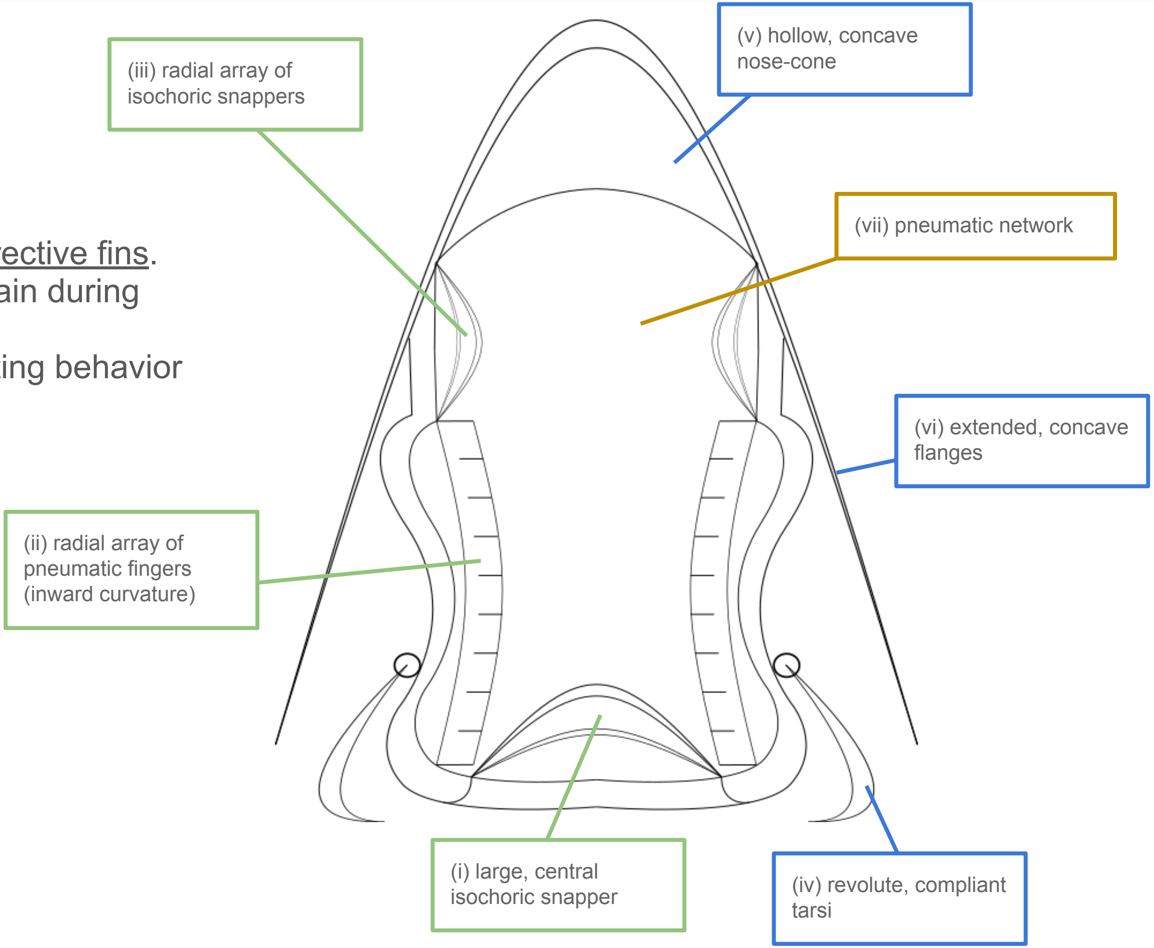
Feature I. Compliant Tarsus:





Design I. Grasshopper Rocket : *mechanical layout*

(i) thruster, generates lift force
(ii) modulatory mechanisms *w.r.t* thruster lift
(iii) assist with pre- and mid-flight corrections; corrective fins.
(iv) these tarsi stabilize and assist w/ gripping terrain during landing
(v) this nose-cone is meant to assist with self-righting behavior
(vi) the flanges are an extension of the nose cone
(vii) pneumatic network (on-board or tethered)



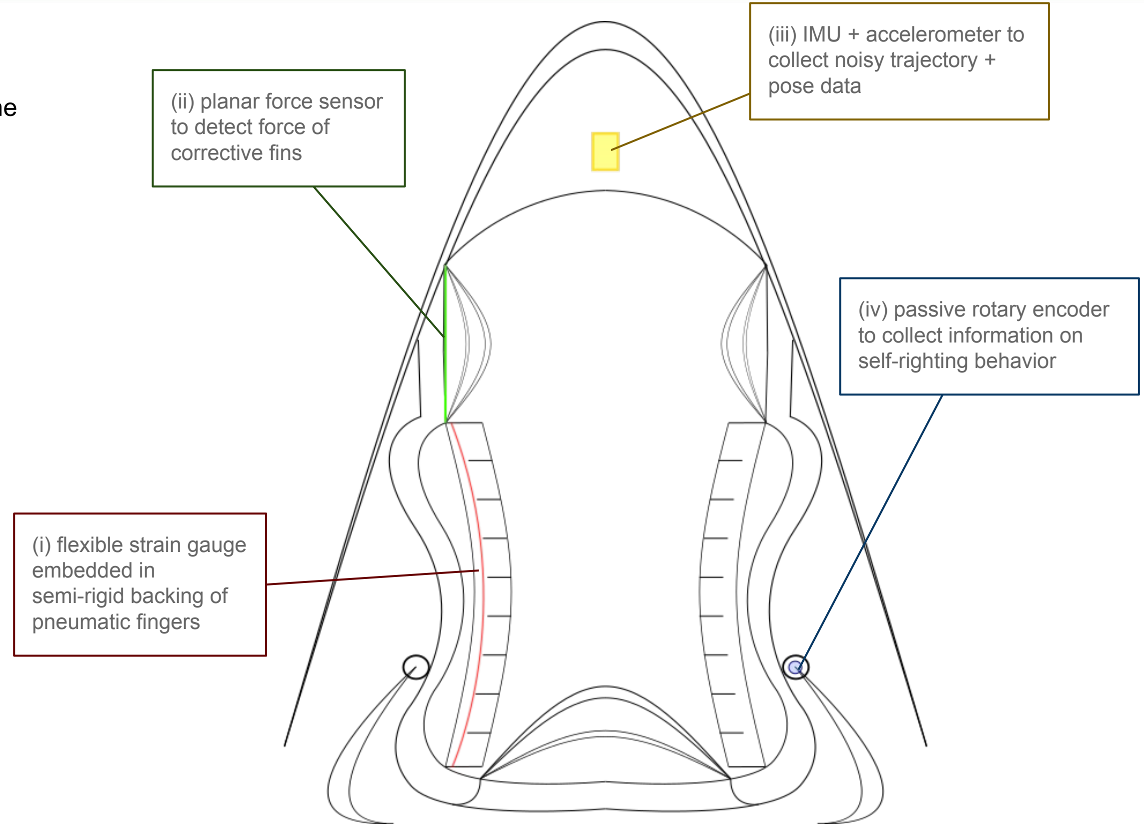
Design I. Grasshopper Rocket : *sensorization*

DATA BY SENSOR:

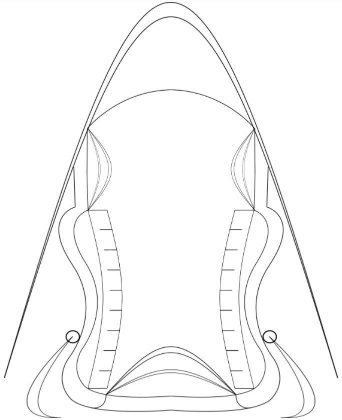
(i) : force caused by finger deflection/bending
(ii) : force of impact of shell snapper's bottom membrane with the device's inner wall due to isochoric instability
(iii) : (x, y, z)-velocity + (x,y,z)-acceleration
(iv) : rotational count for tarsi

COMBINATION OF DATA → BEHAVIOR:

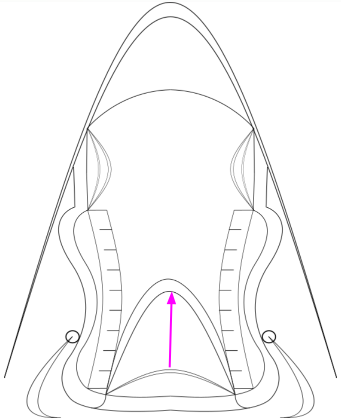
(i) → pre-flight thrust modulation (pfTM)
(ii + iv) → pre-flight correction behavior (pfCB)
(ii + iii) → mid-flight correction behavior (mfCB)
(iii + iv) → self-righting behavior (SRB)



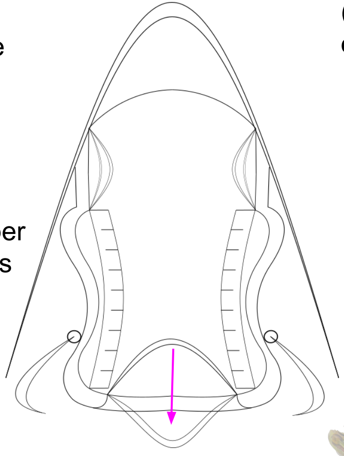
Design I. Grasshopper Rocket: *actuation* + *landing*



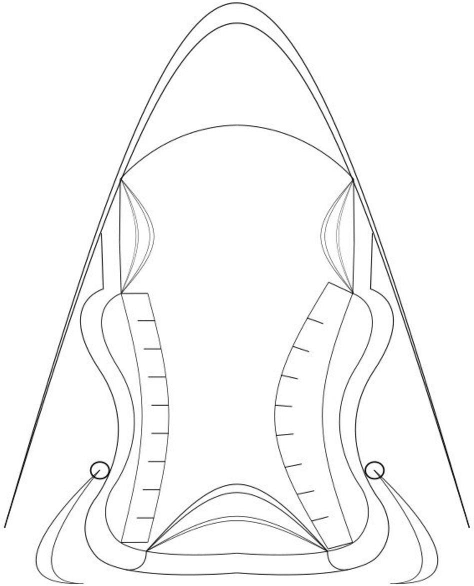
(i) actuator resting state



(ii) inflation of snapper

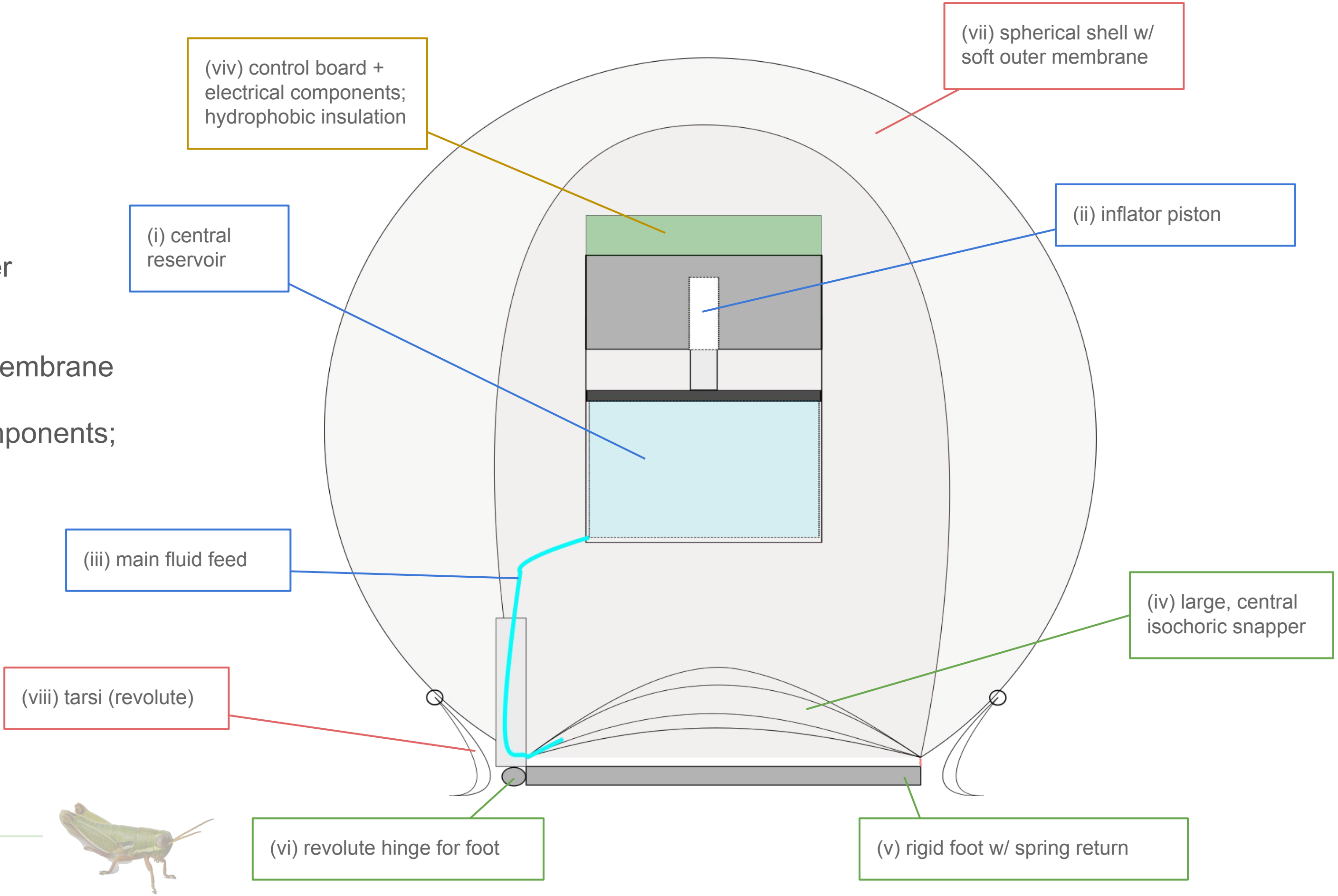


(iii) snapper undergoes buckling instability



Design II. Rigid Foot Transduction : *mechanical layout*

(i) central reservoir
(ii) inflator piston
(iii) main fluid feed
(iv) large, central isochoric snapper
(v) rigid foot w/ spring return
(vi) revolute hinge for foot
(vii) spherical shell w/ soft outer membrane
(viii) tarsi (revolute)
(viv) control board + electrical components; hydrophobic insulation



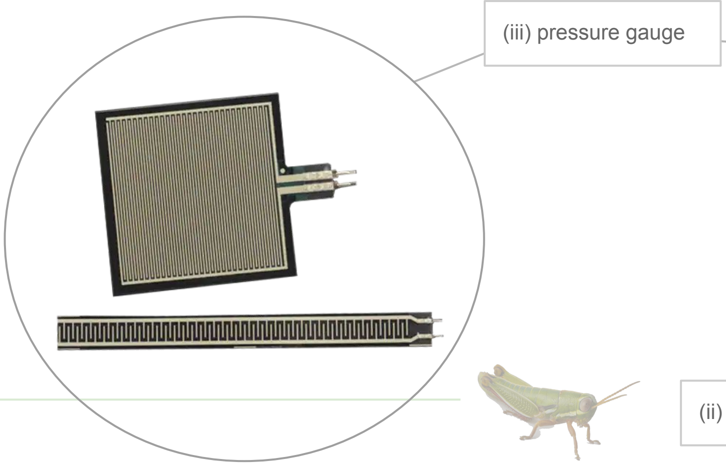
Design II. Rigid Foot Transduction : *sensorization*

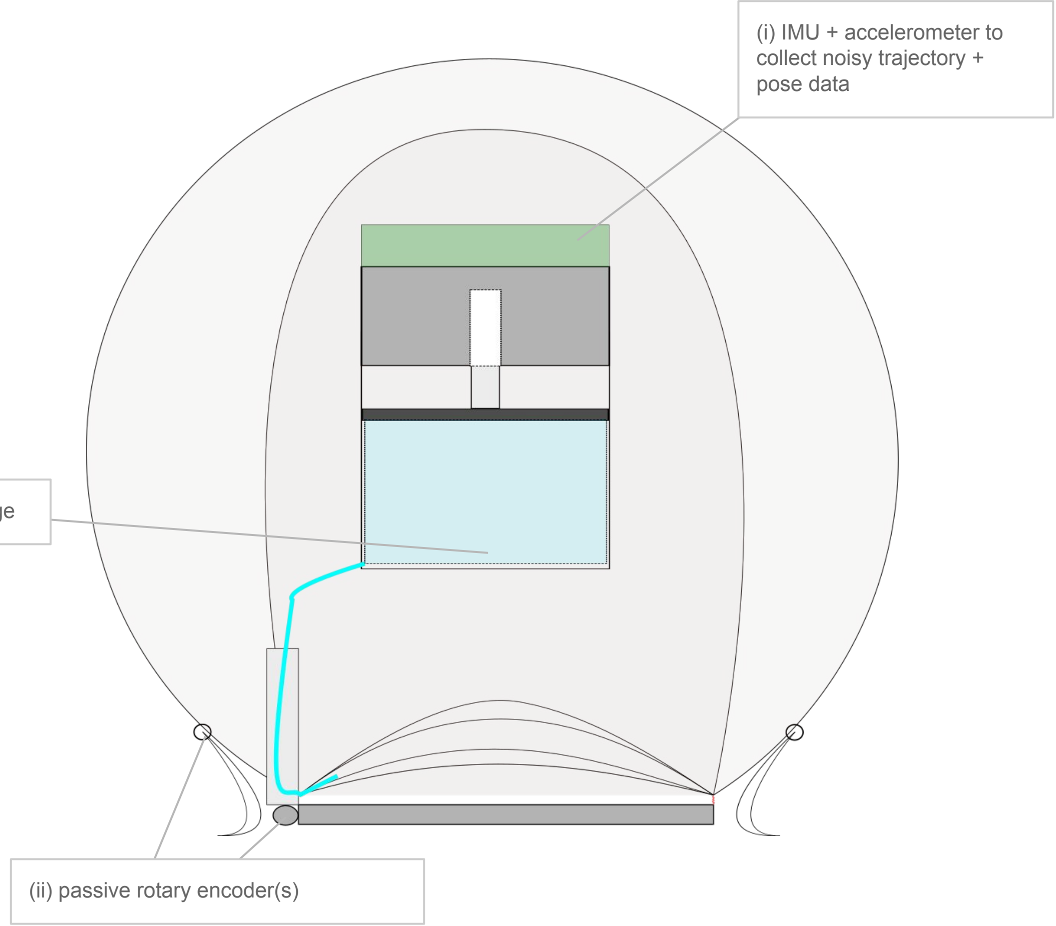
DATA BY SENSOR:

(i) : (x, y, z)-velocity + (x,y,z)-acceleration
(ii) : amount of pressure w/in reservoir
(iii) : rotational count for tarsi

COMBINATION OF DATA → BEHAVIOR:

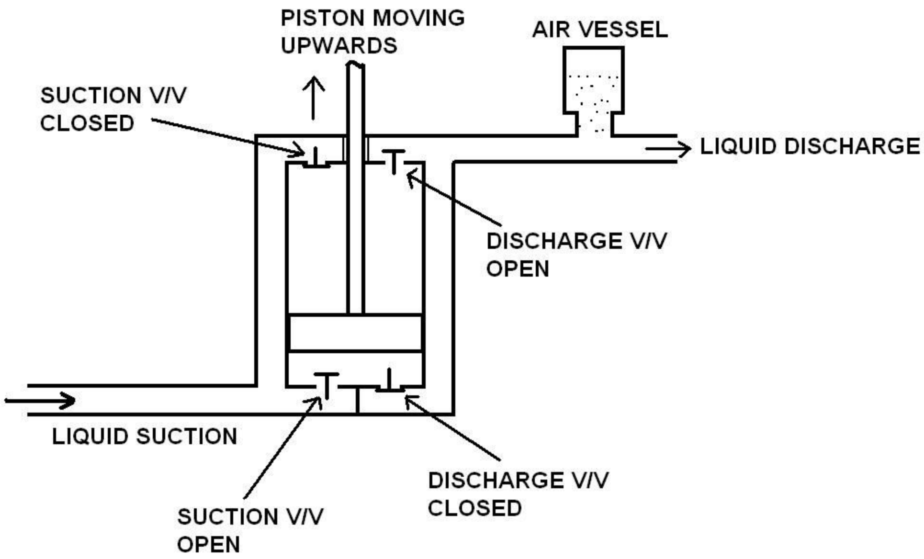
(ii) → mechanical pump/suction (MPS)
(i + iii) → self-righting behavior (SRB)

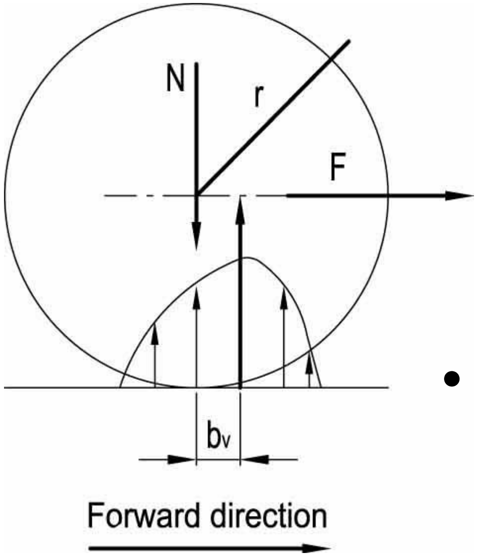




Design II. Rigid Foot Transduction : *behaviors*

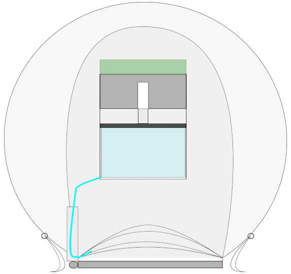
- **mechanical pump/suction** (MPS)
  breaks reliance on tethered PneuNet for actuation and resetting



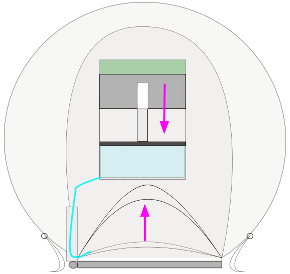


- **self-righting behavior** (SRB)
  approx. spherical; less likely to get stuck in uneven terrain

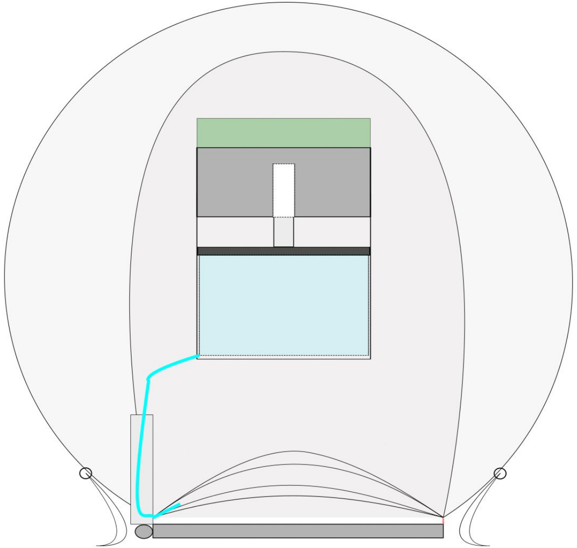
Design II. Rigid Foot Transduction : *actuation + landing sequence*

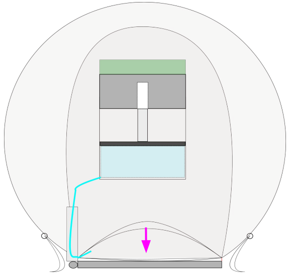


(i) actuator
resting state

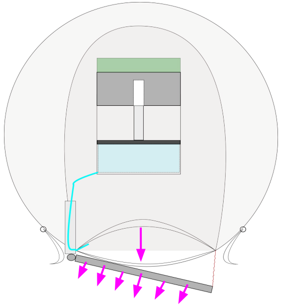


(ii) water pumped
from reservoir into
snapper





(iii) snapper reaches
isochoric limit and
begins to buckle



(vi) lower half-shell
impacts foot; foot
impacts ground

Design Comparison : *issues & extensions*

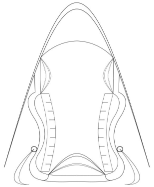
D1: Grasshopper Rocket

D1 ISSUES:

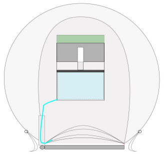
- **Difficult to control!**
  - many component actuators
  - asymmetric buckling of elastics is ongoing topic of research
- **Pneumatic network challenges**
  - bulky; power-intensive (onboard)
  - otherwise tethered

D1 EXTENSIONS:

- **Actuating the tarsi!**
  - would allow for more pre-flight control
  - assist with recovery



D2: Rigid Foot



D2 ISSUES:

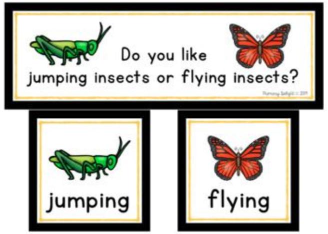
- **Difficult to aim!**
  - not aerodynamic
  - longer jumps → more momentum
    - less precise landing
- **Piston pumps often have trade-off:**
  - expensive or low-pressure
  - cheaper 'homebrew' piston pumps tricky

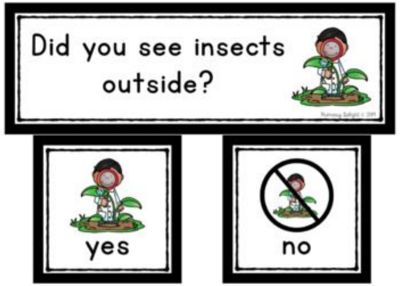
D2 EXTENSIONS:

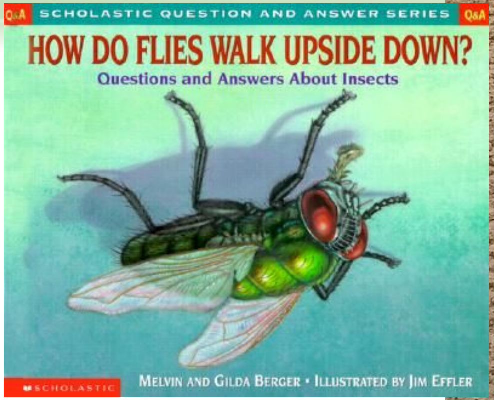
- **Chain them together!**
  - change spherical design → 'orange slice'
  - move controls to center
  - rigid feet radially inward vs. radially outward
- **Inclusion of piezoelectric outer shell**
  - jumping device = repeated impacts
  - similar principle as regenerative brakes

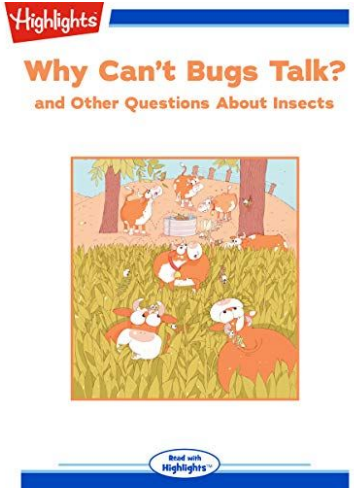
Q & A

- Got questions? *We have answers!*









References

1. Hadley, Debbie. "10 Fascinating Facts About Grasshoppers." ThoughtCo, Aug. 27, 2020, thoughtco.com/fascinating-facts-about-grasshoppers-1968334.
2. https://en.wikipedia.org/wiki/Grasshopper
3. W. J. Heitler, M. Burrows; The locust jump. I. The motor programme. *J Exp Biol* 1 February 1977; 66 (1): 203–219. doi: https://doi.org/10.1242/jeb.66.1.203
4. Hoyle, Graham. "The Leap of the Grasshopper." *Scientific American*, vol. 198, no. 1, 1958, pp. 30–35., www.jstor.org/stable/24942031. Accessed 26 May 2021.
5. W. J. HEITLER; The Locust Jump: III. Structural Specializations of the Metathoracic Tibiae. *J Exp Biol* 1 April 1977; 67 (1): 29–36. doi: https://doi.org/10.1242/jeb.67.1.29
6. Malcolm Burrows, Genevieve Morris; The kinematics and neural control of high-speed kicking movements in the locust. *J Exp Biol* 15 October 2001; 204 (20): 3471–3481. doi: https://doi.org/10.1242/jeb.204.20.3471
7. Sutton, G.P., Burrows, M. The mechanics of elevation control in locust jumping. *J Comp Physiol A* 194, 557–563 (2008). https://doi.org/10.1007/s00359-008-0329-z
8. [1] K. Kral, "Spatial vision in binocular and monocular common field grasshoppers (Chorthippus brunneus)," *Physiol. Entomol.*, vol. 33, no. 3, pp. 233–237, 2008, doi: 10.1111/j.1365-3032.2008.00626.x.
9. [2] D. Hawlena, H. Kress, E. R. Dufresne, and O. J. Schmitz, "Grasshoppers alter jumping biomechanics to enhance escape performance under chronic risk of spider predation," *Funct. Ecol.*, vol. 25, no. 1, pp. 279–288, 2011, doi: 10.1111/j.1365-2435.2010.01767.x.
10. [3] Q. V. Nguyen and H. C. Park, "Design and Demonstration of a Locust-Like Jumping Mechanism for Small-Scale Robots," *J. Bionic Eng.*, vol. 9, no. 3, pp. 271–281, 2012, doi: 10.1016/S1672-6529(11)60121-2.
11. [4] H. Zhang, Z. Gao, X. Ma, J. Zhang, and J. Zhang, "Hybridizing teaching-learning-based optimization with adaptive grasshopper optimization algorithm for abrupt motion tracking," *IEEE Access*, vol. 7, pp. 168575–168592, 2019, doi: 10.1109/ACCESS.2019.2954500.
12. [5] K. Kral, "Comparison of the use of active vision for depth perception in three grasshopper families (Orthoptera: Caelifera)," *Ann. Entomol. Soc. Am.*, vol. 102, no. 2, pp. 339–345, 2009, doi: 10.1603/008.102.0217.
13. [6] L. C. Garro, "Narrative representations of chronic illness experience: cultural models of illness, mind, and body in stories concerning the Temporomandibular Joint (TMJ)," *Soc. Sci. Med.*, vol. 38, no. 6, pp. 775–788, 1994, doi: 10.1016/0277-9536(94)90150-3.
14. [7] A. Pal, V. Restrepo, D. Goswami, and R. V. Martinez, "Exploiting Mechanical Instabilities in Soft Robotics: Control, Sensing, and Actuation," *Adv. Mater.*, p. 2006939, 2021, doi: 10.1002/adma.202006939.
15. [8] M. Ilami, H. Bagheri, R. Ahmed, E. O. Skowronek, and H. Marvi, "Materials, Actuators, and Sensors for Soft Bioinspired Robots," *Adv. Mater.*, 2020, doi: 10.1002/adma.202003139.
16. [9] S. Kagechika, Y. Iwatani, K. Tsurui, and A. Honma, "A robotized system for encouraging grasshoppers to jump," *Proc. SICE Annu. Conf.*, pp. 572–577, 2014, doi: 10.1109/SICE.2014.6935210.
17. [10] A. Konez, "Development and Analysis of Grasshopper-like Jumping Mechanism in Biomimetic Approach," 2007.
18. [11] A. Konez, "Preliminary Mechanism Design Analysis Like-Grasshopper," no. September, 2006.
19. [12] E. J. Queathem and R. J. Full, "Variation in jump force production within an instar of the grasshopper Schistocerca americana," *J. Zool.*, vol. 235, no. 4, pp. 605–620, 1995, doi: 10.1111/j.1469-7998.1995.tb01772.x.
20. [13] K. Tsurui, S. Narita, Y. Iwatani, and A. Honma, "Change in take-off elevation angle after limb autotomy mitigates the reduction in jumping distance in rice grasshoppers Oxya yezoensis," *Entomol. Sci.*, vol. 17, no. 2, pp. 181–190, 2014, doi: 10.1111/ens.12054.
21. [14] K. Kral, "Similarities and differences in the peering-jump behavior of three grasshopper species (orthoptera: caelifera)," *Insect Sci.*, vol. 15, no. 4, pp. 369–374, 2008, doi: 10.1111/j.1744-7917.2008.00223.x.
22. [15] C. Bielmeier, "Exploration of an electroactive polymer actuator for application in a grasshopper inspired pneumatic robotic hopper ACTUATOR FOR APPLICATION IN A GRASSHOPPER INSPIRED By," 2003.
23. [16] S. L. Giampalmo *et al.*, "Generation of complex motor patterns in american grasshopper via current-controlled thoracic electrical interfacing," *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, pp. 1275–1278, 2011, doi: 10.1109/IEMBS.2011.6090300.
24. [17] B. Gorissen, D. Melancon, N. Vasios, M. Torbati, and K. Bertoldi, "Inflatable soft jumper inspired by shell snapping," *Sci. Robot.*, vol. 5, no. 42, 2020, doi: 10.1126/SCIROBOTICS.ABB1967.
25. [18] "SNAPPING SHELLS AND ELASTOGRANULAR," 2019.
26. [19] D. Karagiozova, X. W. Zhang, and T. X. Yu, "Static and dynamic snap-through behaviour of an elastic spherical shell," *Acta Mech. Sin. Xuebao*, vol. 28, no. 3, pp. 695–710, 2012, doi: 10.1007/s10409-012-0065-z.
27. [20] S. Ippili *et al.*, "An eco-friendly flexible piezoelectric energy harvester that delivers high output performance is based on lead-free MASnI 3 films and MASnI 3 -PVDF composite films," *Nano Energy*, vol. 57, no. September 2018, pp. 911–923, 2019, doi: 10.1016/j.nanoen.2019.01.005.
28. [21] G. P. Sutton and M. Burrows, "The mechanics of elevation control in locust jumping," *J. Comp. Physiol. A Neuroethol. Sensory, Neural, Behav. Physiol.*, vol. 194, no. 6, pp. 557–563, 2008, doi: 10.1007/s00359-008-0329-z.
29. https://www.elesa.com/en/CatalogoDatiTecniciOC/42-rolling-friction
30. https://fiberlogy.com/en/fiberlogy-filaments/impact-pla/
31. https://www.st-andrews.ac.uk/~wjh/jumping/contents.html
32. https://www.researchgate.net/publication/326439672_Dynamics_of_viscoelastic_snap-through/figures?lo=1&utm_source=google&utm_medium=organic

APPENDIX

Grasshopper fun facts

- Typically about 5cm long
- Existed long before dinosaurs

ThoughtCo.

Grasshopper fun facts

- Huge delicacy in some parts of the world

Chapulines dish in Mexico

Sweet-and-salty grasshoppers dish in Japan (*Inago no Tsukudani*)

ThoughtCo.
Wikipedia contributors

Grasshopper fun facts

- Huge delicacy in some parts of the world
- They make ‘music’ by stridulating

Sweet-and-salty grasshoppers dish in Japan (*Inago no Tsukudani*)

Chapulines dish in Mexico

ThoughtCo.
Wikipedia contributors

Why is this important?

For grasshoppers

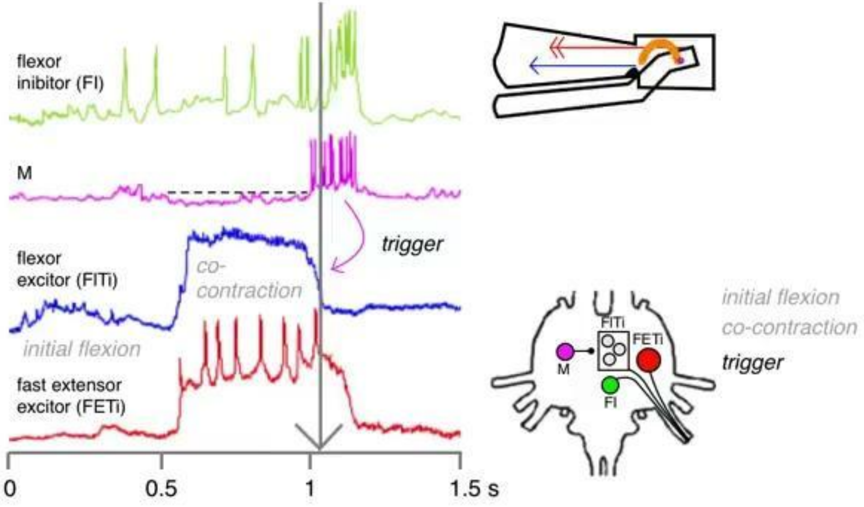
- Flee from a predator
- Launch themselves into flight
- To move from place to place

This can inspire the creation of robots

- To cover shorter distances
- Move in complex

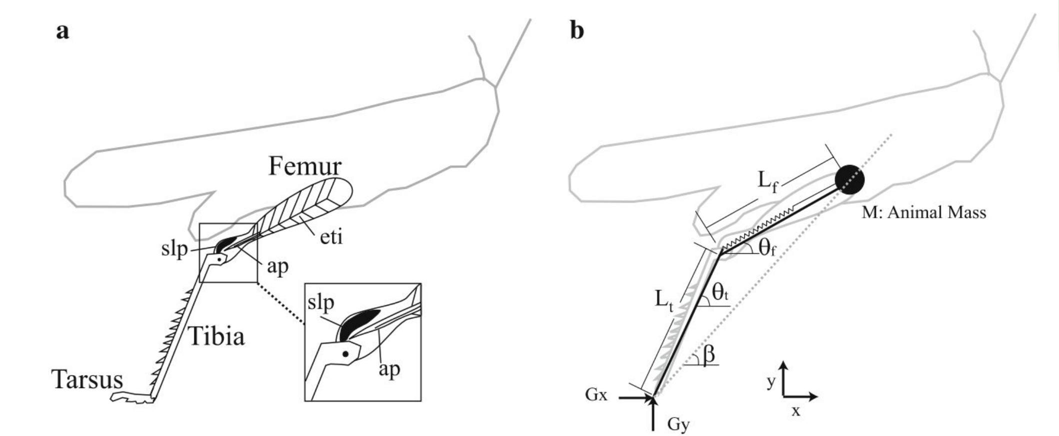
The neurobiology of the jump

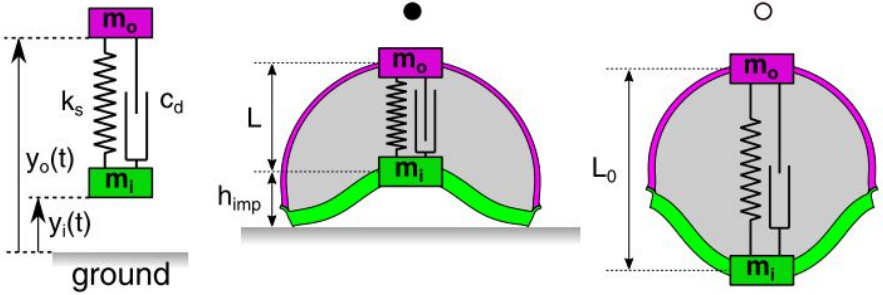
- Ventral cord runs through its length
- Each segment is controlled by its own ganglion
- Metathoracic ganglion controls the hind legs
    - Fast extensor excitor (FETi)
    - Flexor excitor (FITi)
    - Flexor inhibitor, FI
    - Multimodal interneuron, M



Heitler and Burrows, 1977

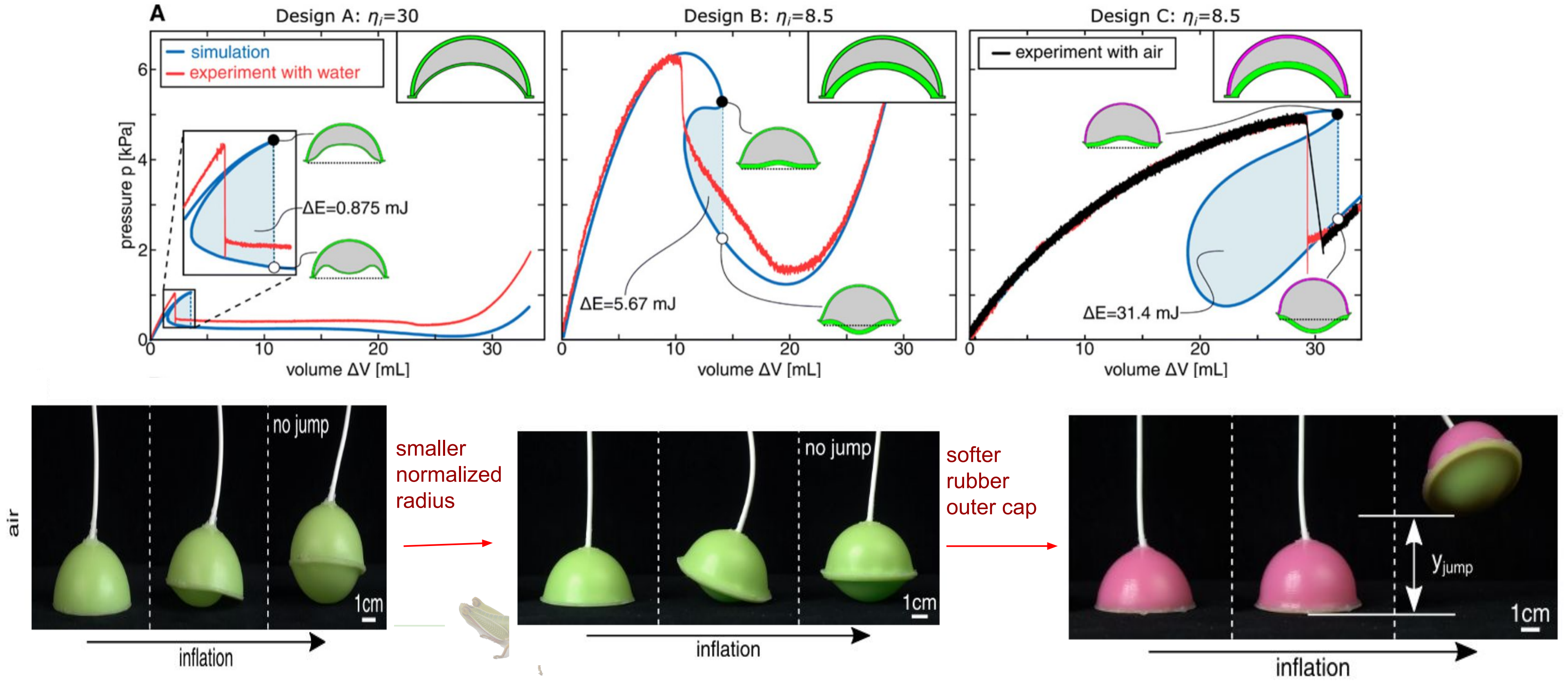
Mechanical approximation





Isochoric Snapping Actuators

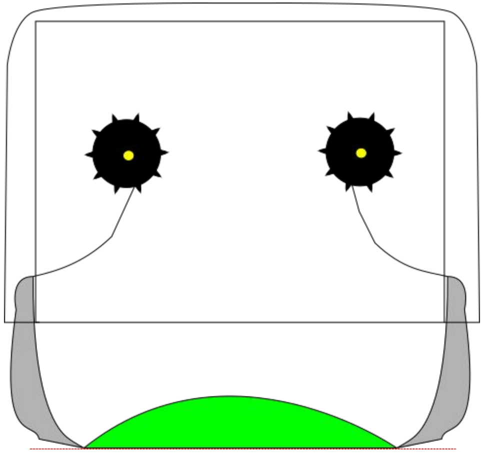
- The geometry and the type of material are crucial for controlling isochoric snapping

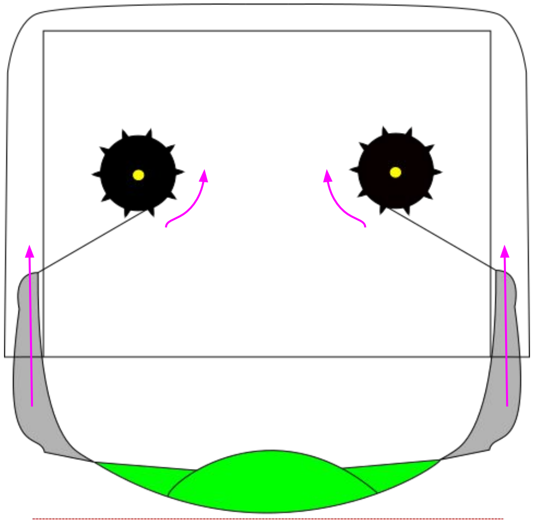


Thought Experiment (Single Membrane Snapper):

NOT ENOUGH FORCE

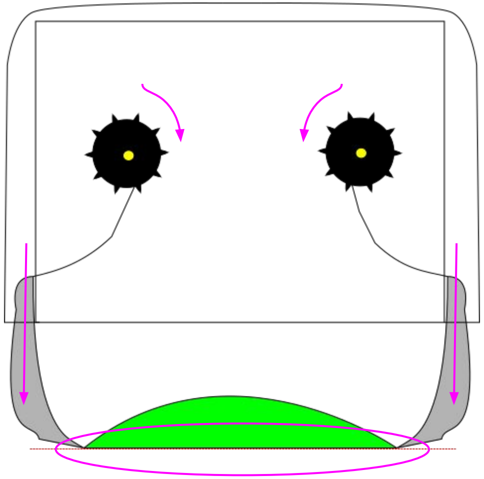
(i) actuator resting state





(ii) pulleys invert soft shell membrane

(iii) pulleys slacken, soft shell membrane undergoes buckling instability when coming into contact with ground



https://slidesgo.com/theme/national-trails-day#search-Nature&position-13&results-18

https://slidesgo.com/theme/inspirational-green#search-Nature&position-9&results-18

https://slidesgo.com/theme/calms-presentation#position-2

https://slidesgo.com/theme/koro-business-plan#search-Green&position-17&results-18

Outline

- Bio side of the grasshopper jumping mechanism
  - Why is this important? Why is this cool?
- Explanation of isochoric snapping actuator
  - Explanation of isochoric instability
    - NOTE: don’t go too deep into the math; focus on applications and parameter trade-off
    - EXTRA: single wall vs. double wall
  - Tie-in to grasshopper jumping
    - Why use an isochoric snapper?
      - Similarities and differences between snapper and grasshopper jumping mechanism (leg muscle complex?)
      - EXTRA: trade-offs between mechanical actuators to model jumping mechanism
- Designs
  - Requirements and desired features
  - Present different designs
    - Explain function
    - Explain limitations
    - EXTRA: any sort of simulated data
  - Explain trade-offs in summary slide
  - Explain which one we think is best

Possible presentation flow - outline

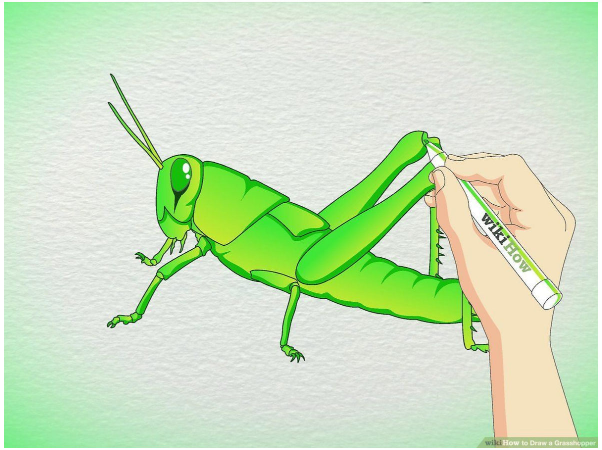
- Why is this relevant?
    - How well can a grasshopper/locust jump?
    - What is the significance of that ability
        - Possible applications of that
    - Now that we know why this is important and the possible applications, how is the grasshopper able to achieve this?
        - The mechanical basis, muscle force generated …
        - How energy is stored and dissipated to propel them forward
- Designing the soft robot
    - Biomimetic vs. bio-inspired ~(form vs. function)
    - Utilizing instability (e.g., buckling varieties)

Presentation Outline

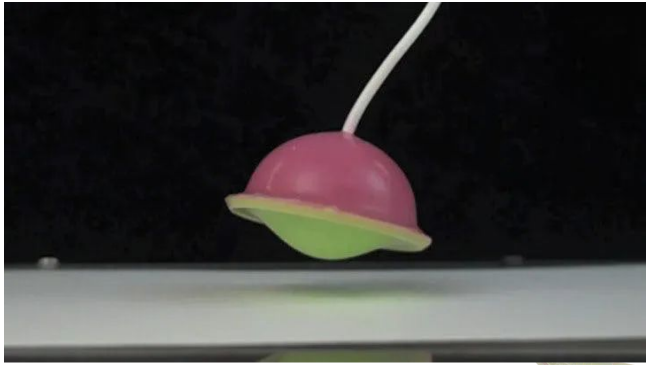
- Part I:
  - Introduction to grasshoppers
  - Jumping mechanism of the grasshopper
- Part II:
  -

Requirements & Challenges

Bio-inspired:



- **bR1:** *Alter initial trajectory* (cocking phase)
- **bR2:** *Modulate* different muscle groups (co-contraction phase)
- **bR3:** *Release energy stored* (triggering phase)



Mechanical:

- **mR1:** *Model impact force* between a rigid plane and snapper
- **mR2:** *Model the effect of mechanical deformation* on the top spherical half-shell of an isochoric snapper
- **mR3:** *Model* (*and control*) *the timing of multiple soft actuator cells* driven by non-compressible fluid(s)

Design I. Grasshopper Rocket: *behaviors*

- **pre-flight thrust modulation** (pfTM)
  deformation of the snapper's upper half-shell allows for difference buckling behavior

- **pre-flight correction behavior** (pfCB)
  lateral (to device frame) force generated by fins 'jostle' tarsi, repositioning the device

- **mid-flight correction behavior** (mfCB)
  lateral force generated by fins can equally cause mid-flight trajectory deflections

- **self-righting behavior** (SRB)
  convex chassis + flanges encourage tipping towards base