October 20, 2025

PhD in BioRobotics

Course of
Principles of Bionics and Biorobotics Engineering

Lesson title:

Jumping Locomotion

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Jumping locomotion

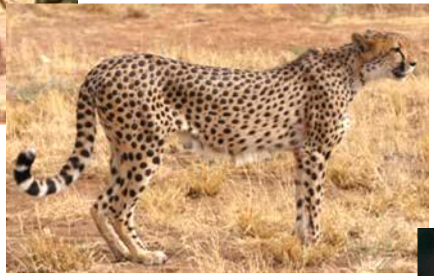
Exploring effective locomotion strategies in the small scale (millimeter size) in terms of:

- Energy efficiency

- Negotiation of uneven terrains

- Robustness to disturbances (e.g.: wind when only flying)

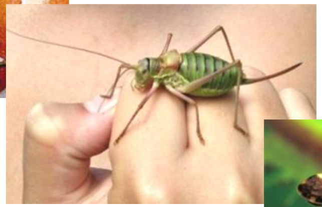
Jumping in small animals

By investigating **scale effects** on locomotion in different sized animals, it results that the choice of the optimal gait strongly depends upon animal dimensions.

For small animals that have to travel rapidly on ground, jumping rather than walking is the only physical solution.


Less interaction with ground, less dissipated power




It is observed that different sized animals switch from walk to run (or trot if quadruped) at the same ***Froude Number*** $F_r \approx 0.4$ [1-2]. The change in gait is driven by energetic choice of the most efficient gait [3] .

$$F_r = \frac{v^2}{gl}$$

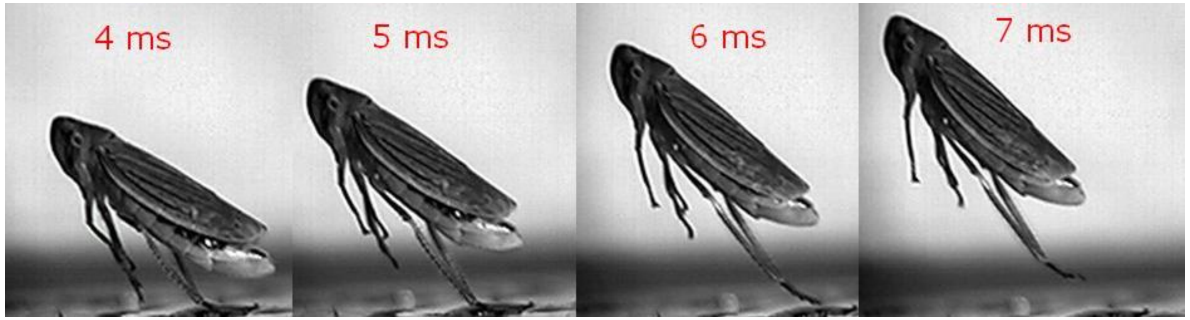
[1] R.M. Alexander, Principles of animal locomotion, Princeton University Press, (2003)

[2] C.T. Farley, C.R. Taylor, A mechanical trigger for the trot–gallop transition in horses, *Science*, 253, 306–308, (1991)

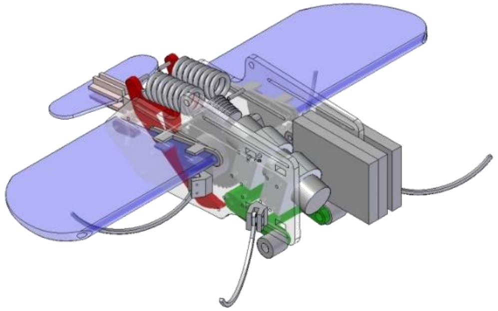
[3] R.M. Alexander, Energetics and Optimization of Human Walking and Running: The 2000 Raymond Pearl Memorial Lecture (2000)

Studying jump locomotion in insects

1. To better understand – from an engineering point of view – the biological mechanisms underlying jumping locomotion in order to extract good design principles



2. To develop a jumping minirobot with onboard power source and ability to travel long distances on uneven terrains



Jumping Insect - Motivation

Established that:

jumping is the only physical solution to travel rapidly on the ground for small animals among small jumpers, **insects** have evolved different mechanism for jumping for escape form predators or launch into flight

We decide to deepen the analysis of

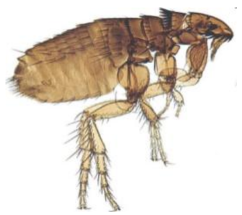
Jumping strategy in insects

Crickets

(Orthoptera, Ensiphera)

Grasshoppers

(Orthoptera, Caeliphera)



Fleas

(Siphonaptera)

Flea-Beatles

(Coleoptera, Alticinae)

Frog-hopper

(Hemiptera, Cercopidae)

Leaf-hoppers

(Hemiptera, Cicadellidae)

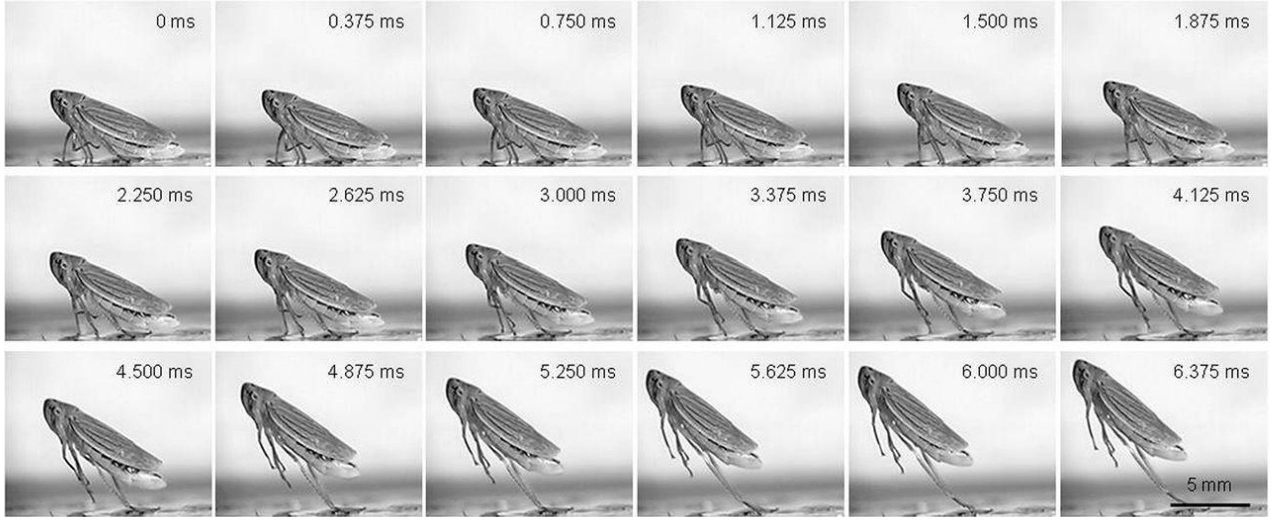
Mo, X., Ge, W., Miraglia, M., Inglese, F., Zhao, D., Stefanini, C., & Romano, D. (2020). Jumping locomotion strategies: from animals to bioinspired robots. Applied Sciences, 10(23), 8607.

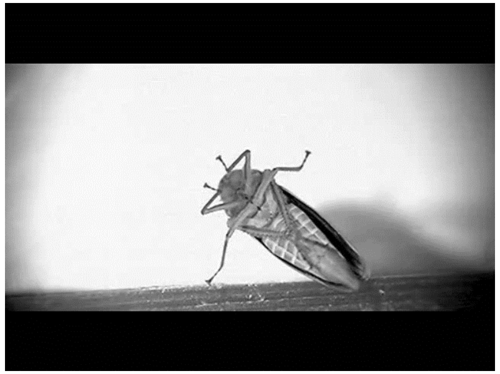
Experimental observation of animal models

Insects collection

Insects rearing

Insects study

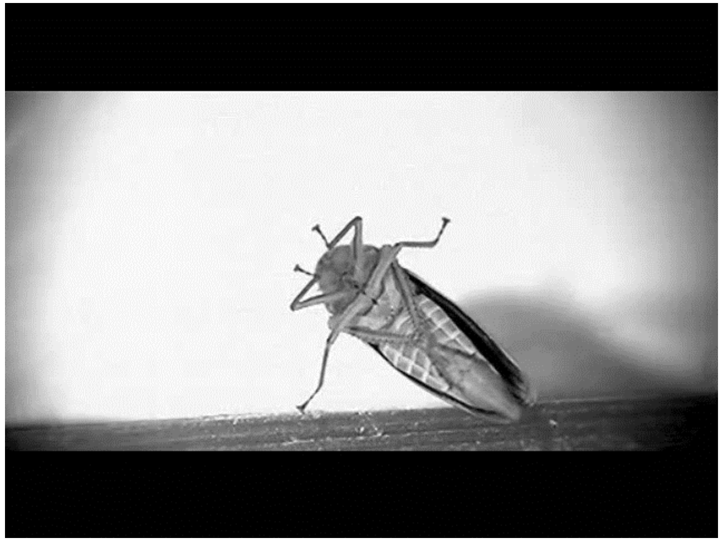




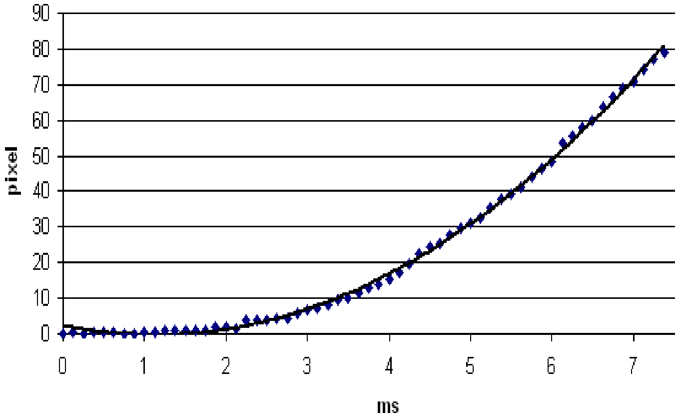
High speed camera (8000 fps)

Bonsignori, G., Stefanini, C., Scarfogliero, U., Mintchev, S., Benelli, G., & Dario, P. (2013). The green leafhopper, Cicadella viridis (Hemiptera, Auchenorrhyncha, Cicadellidae), jumps with near-constant acceleration. *Journal of Experimental Biology*, *216*(7), 1270-1279.

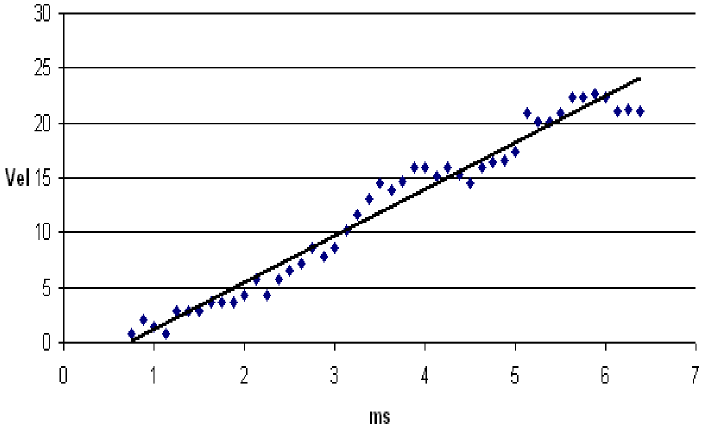
From experimental observation to modeling



Position

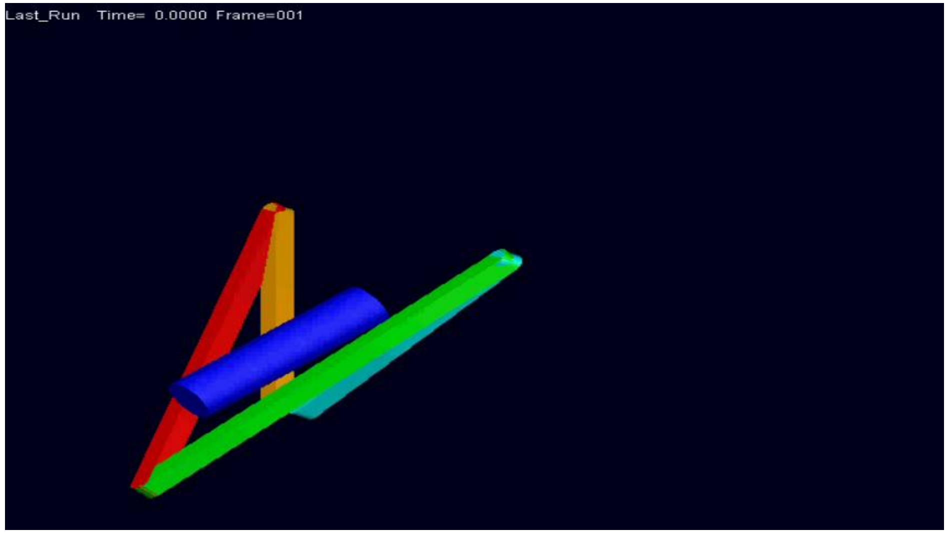


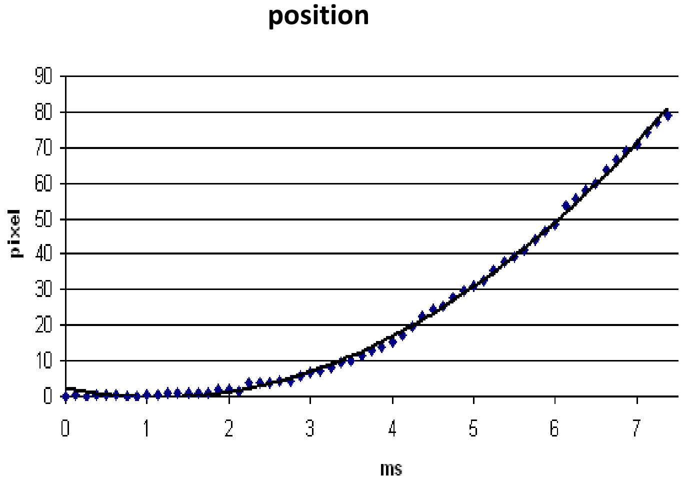
Speed (mm/ms)

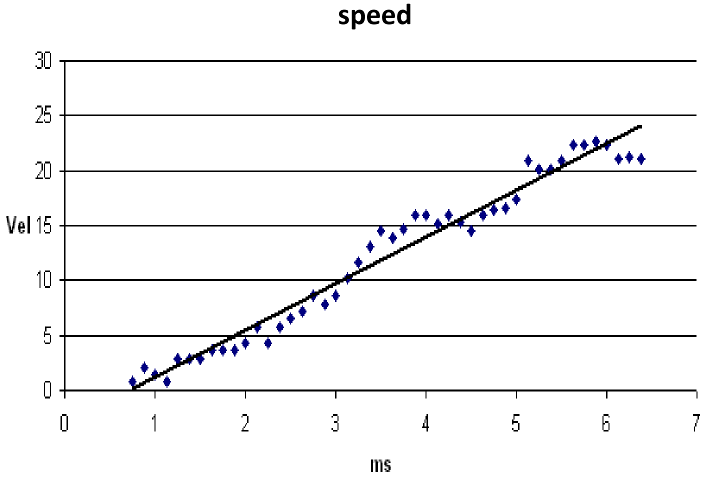


From experimental observation to modeling

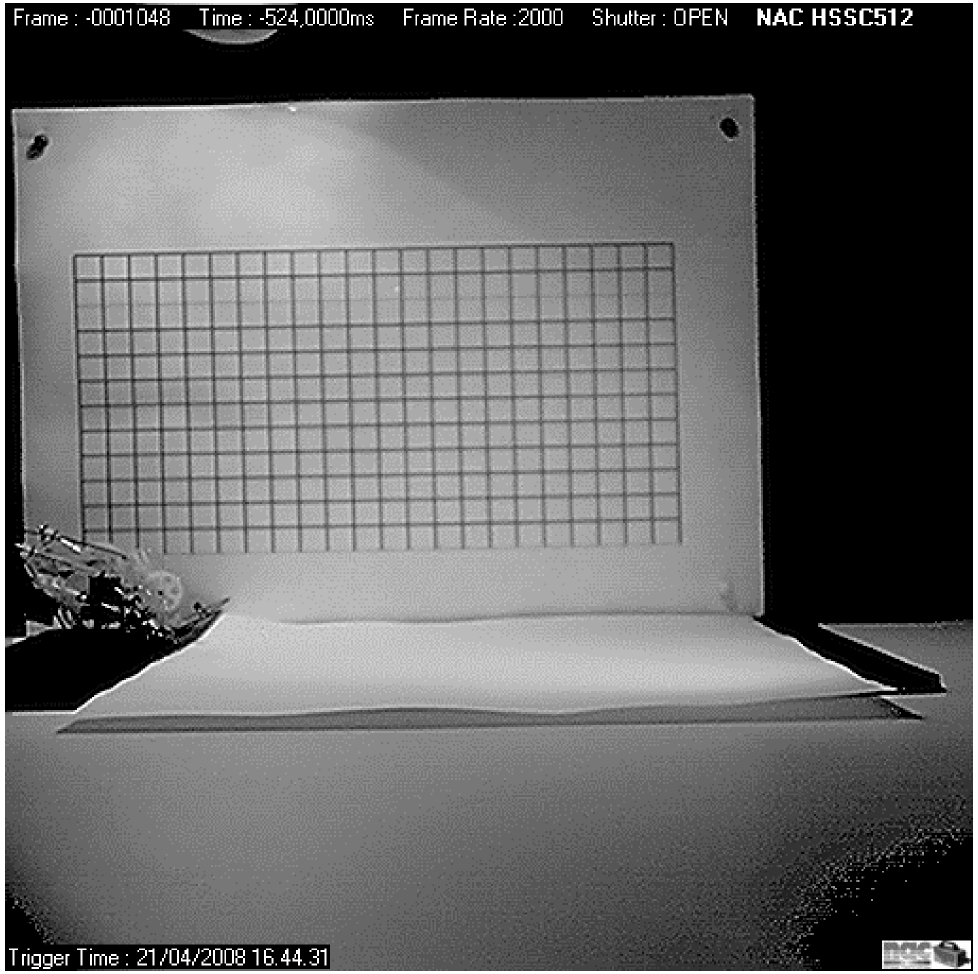
In *C. viridis*, during take-off the legs exert on the ground a fairly constant force, bringing the body to take-off speed in 4-6 ms with a **constant acceleration**





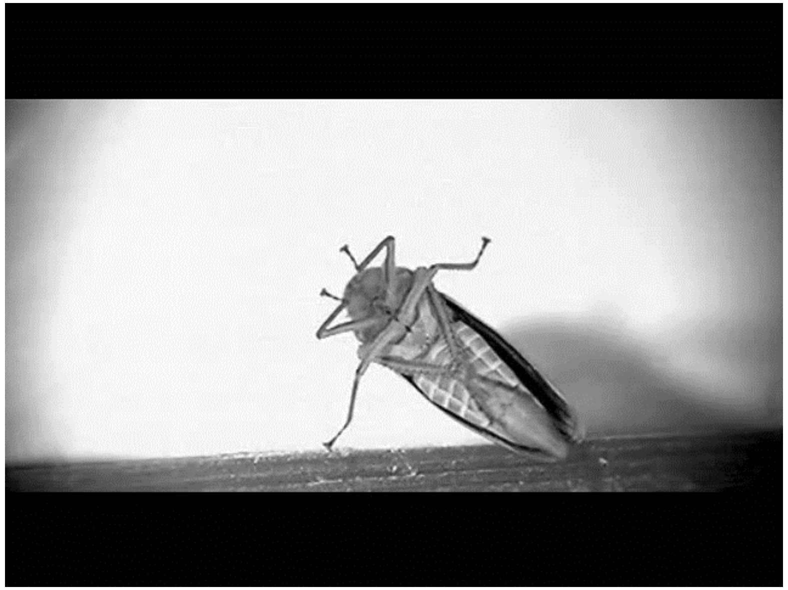


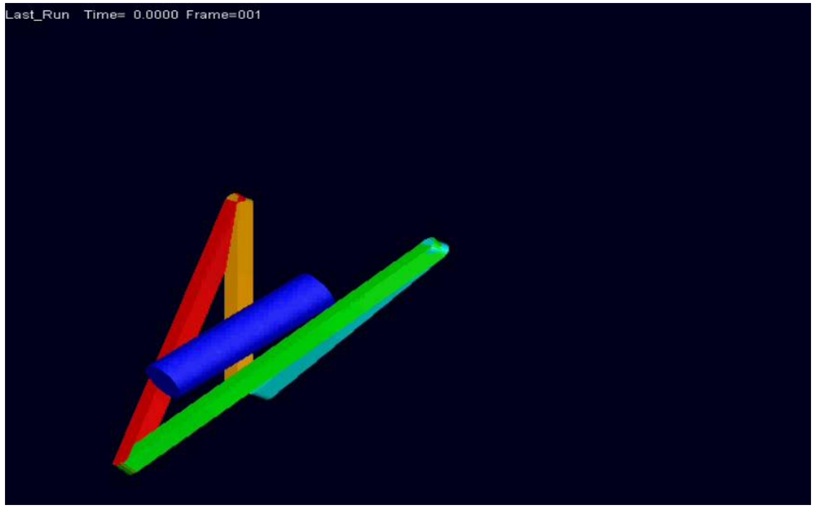
An artifact jumping like an insect



Li, F., Liu, W., Fu, X., Bonsignori, G., Scarfogliero, U., Stefanini, C., & Dario, P. (2012). Jumping like an insect: Design and dynamic optimization of a jumping mini robot based on bio-mimetic inspiration. *Mechatronics*, *22*(2), 167-176.

Jumping animals and robots





High speed camera (8000 fps)

Entomologia Generalis, Vol. 38 (2019), Issue 4, 317–332 **Article**
Published in print March 2019

Modelling jumping in *Locusta migratoria* and the influence of substrate roughness

Xiaojuan Mo[1], Wenjie Ge[1,§], Donato Romano[2], Elisa Donati[3], Giovanni Benelli[2,4,*], Paolo Dario[2] and Cesare Stefanini[2,5]

Table 1. Roughness features of the two types of surfaces used for the experiments.

	L (mm)	R_a (µm)	R_z (µm)
Acrylic surface	3	0.049 ± 0.006	0.362 ± 0.047
Foam surface	10	10.648 ± 2.064	67.917 ± 13.160

L = evaluation length; Ra = roughness value; Rz = average of the ten highest peaks and the ten deepest valleys. Data are presented as mean values±SD.

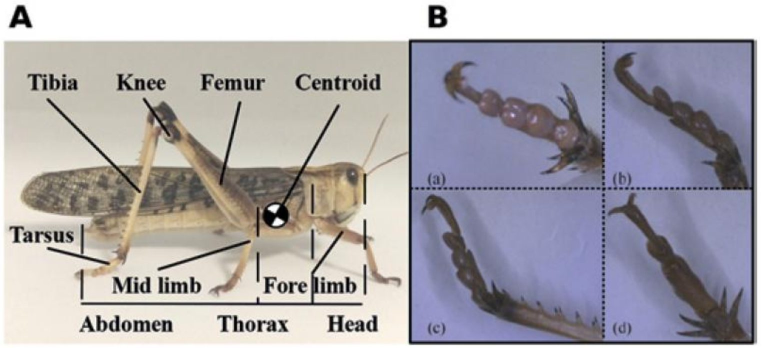


Fig. 1. A: Locust general morphology. **B:** Different views of locust hind legs tarsus: (a) ventral view; (b) external lateral view: (c) internal lateral view; (d) dorsal view.

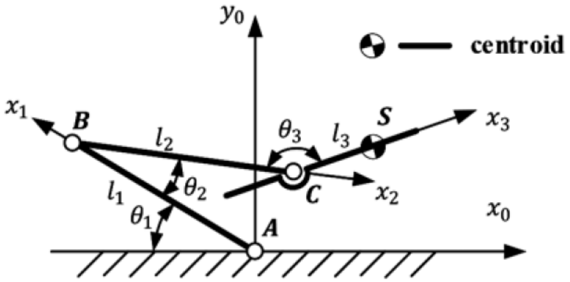


Fig. 2. Theoretical model of locust jumping movements.

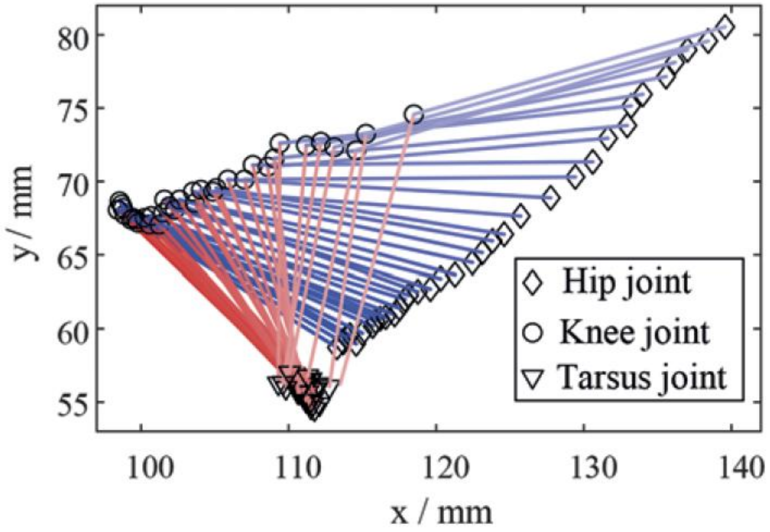


Fig. 3. Trajectories of locust hind legs during take-off.

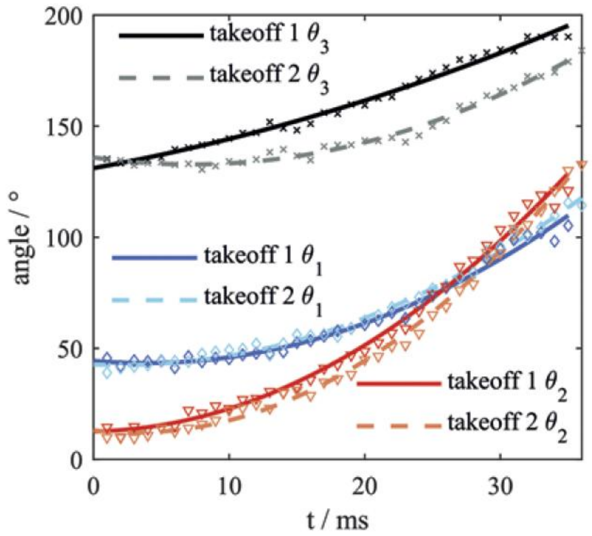
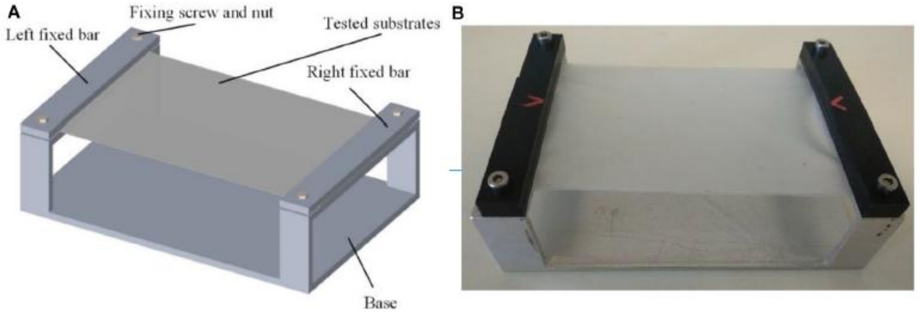


Fig. 4. Angle variation trend during the locust take-off phase.

Effect of Substrates’ Compliance on the Jumping Mechanism of *Locusta migratoria*

Locusts generally live and move in complex environments including different kind of substrates, ranging from compliant leaves to stiff branches. Since the contact force generates deformation of the substrate, a certain amount of energy is dissipated each time a locust jumps from a compliant substrate. In published researches, it is proven that only tree frogs are capable of recovering part of the energy that had been accumulated in the substrate as deformation energy in the initial pushing phase, just before leaving the ground. The jumping performances of adult *Locusta migratoria* on substrates of three different compliances demonstrate that locusts are able to adapt their jumping mode to the mechanical characteristics of the substrate. Recorded high speed videos illustrate the existence of deformed substrate’s recoil before the end of the takeoff phase when locusts jump from compliant substrates, which indicates their ability of recovering part of energy from the substrate deformation. This adaptability is supposed to be related to the catapult mechanism adopted in locusts’ jump thanks to their long hind legs and sticky tarsus. These findings improve the understanding of the jumping mechanism of locusts, as well as can be used to develop artifact outperforming current jumping robots in unstructured scenarios.

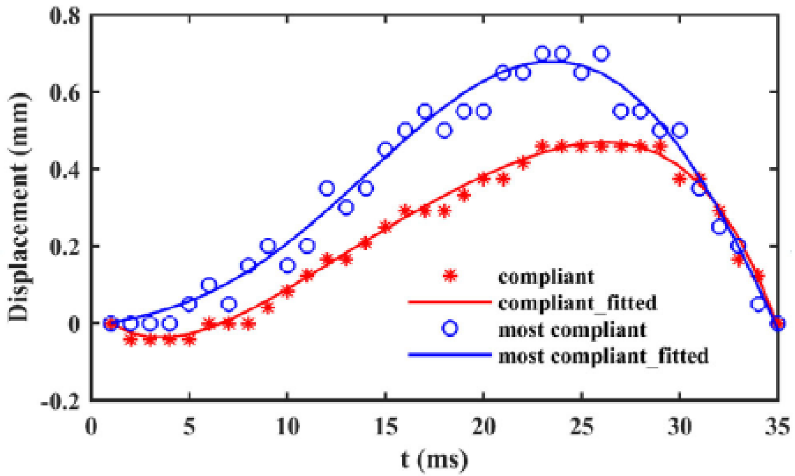


Test bench illustration. **(A)** Test bench 3D model **(B)** Fabricated tested bench.

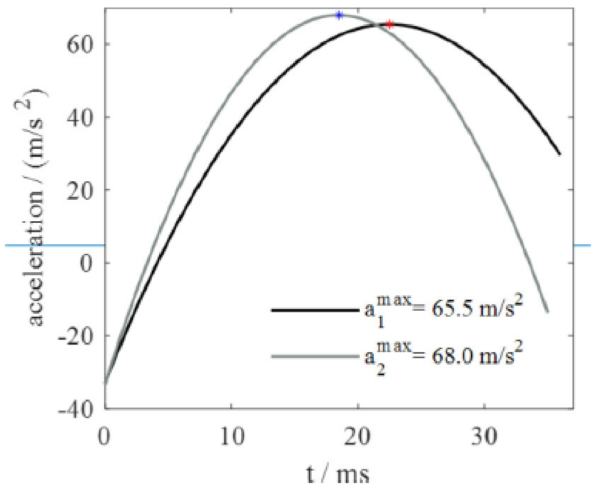
Roughness values and mechanical properties of the two types of substrates used in the experiments.

	Tested length (mm)	Ra (um)	Rz (um)	E (MPa)	ν (pure number)
Membrane	3.000	0.525 ± 0.027	4.076 ± 0.319	~ 5	~ 0.5
Aluminum	3.000	0.113 ± 0.004	1.345 ± 0.211	7.2×10^4	0.334

Ra, roughness value; Rz, average of the ten highest peaks and the ten deepest valleys, E, young's modulus, ν, poisson's ratio.



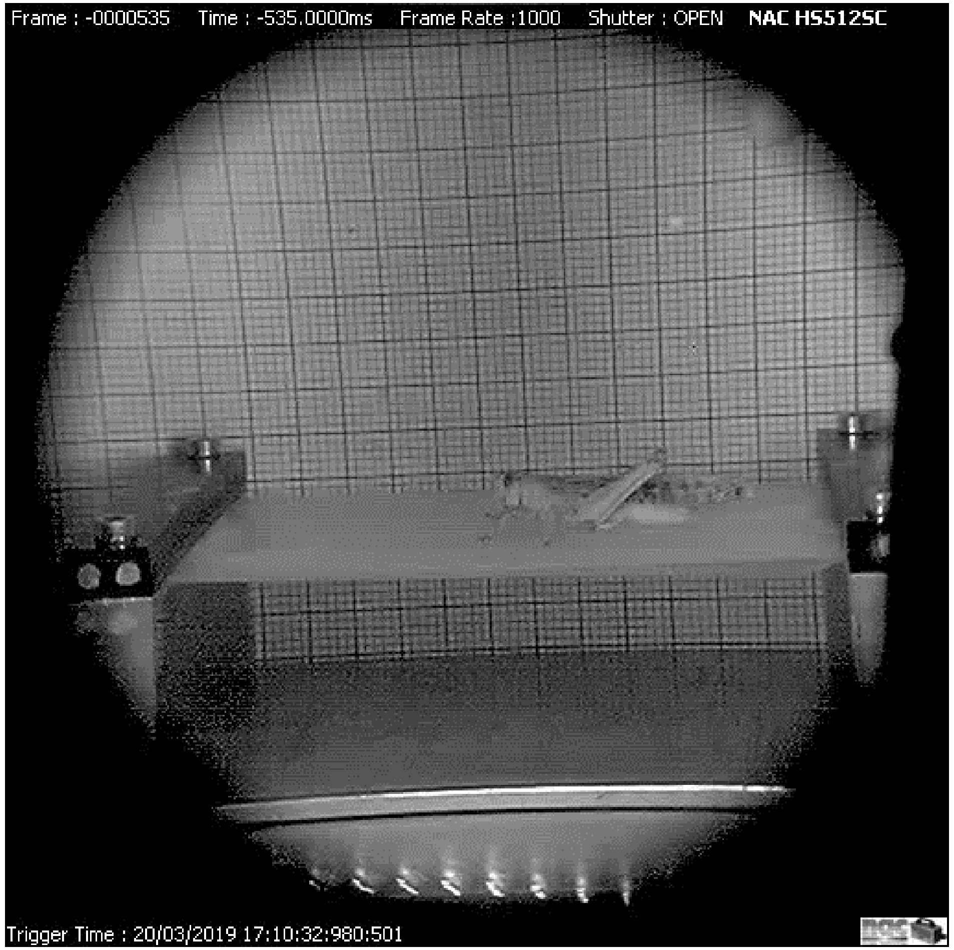
The vertical displacement over time of compliant and most compliant substrates in contact point.



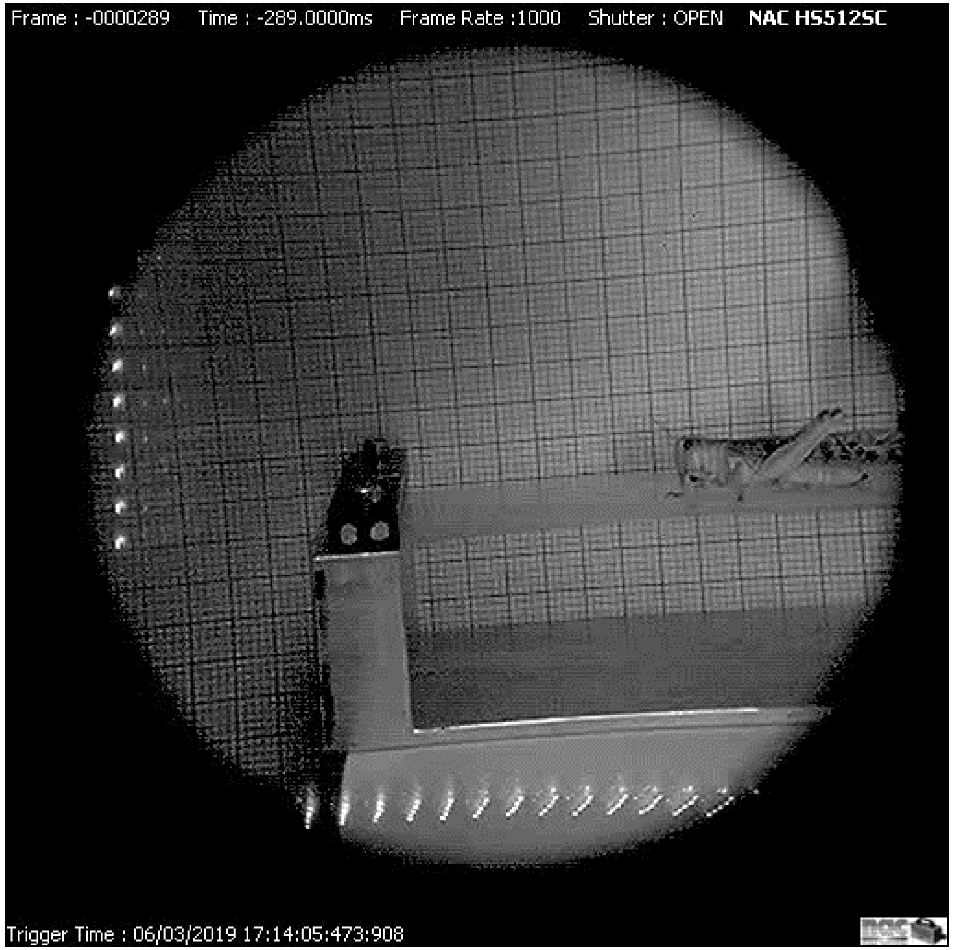
Acceleration trend during takeoff phase: a_1 on a rough foam surface, a_2 on a smooth acrylic surface.

Mo, X., Romano, D., Miraglia, M., Ge, W., & Stefanini, C. (2020). Effect of substrates' compliance on the jumping mechanism of *Locusta migratoria*. Frontiers in Bioengineering and Biotechnology, 8, 661.

Takeoff from compliant substrates



Takeoff from more compliant substrates



Mo, X., Romano, D., Miraglia, M., Ge, W., & Stefanini, C. (2020). Effect of substrates' compliance on the jumping mechanism of *Locusta migratoria*. Frontiers in Bioengineering and Biotechnology, 8, 661.

THE BIOROBOTICS INSTITUTE

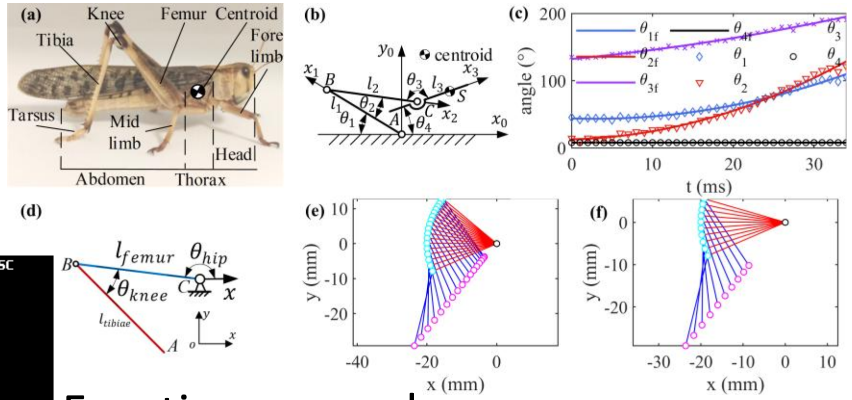
Sant'Anna School of Advanced Studies – Pisa

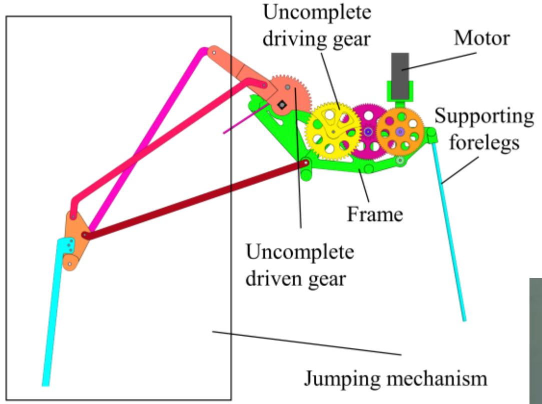
RESEARCH PAPERS

Locust-Inspired Jumping Mechanism Design and Improvement Based on Takeoff Stability

ASME DIGITAL COLLECTION
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Journal of Mechanisms and Robotics

Xiaojuan Mo, Wenjie Ge, Yifei Ren, Donglai Zhao, Dunwen Wei, Donato Romano

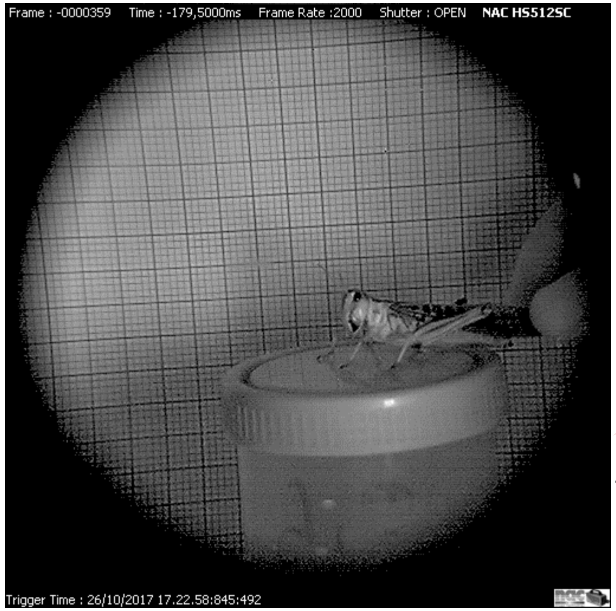




Frontier research

Product innovation

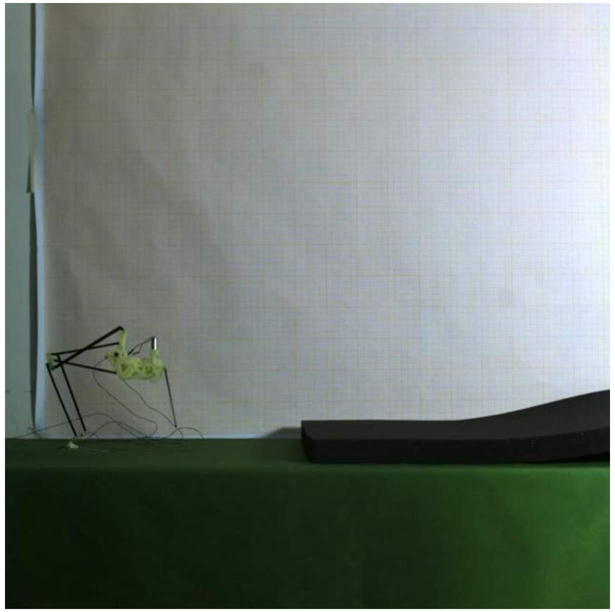
HYPOTHESIS AND MODEL



PHENOMENON
TO BE EXPLAINED

Validation of the model

IMPLEMENTATION
IN A ROBOT



Mo, X., Ge, W., Ren, Y., Zhao, D., Wei, D., & Romano, D. (2024). Locust-inspired jumping mechanism design and improvement based on takeoff stability. Journal of Mechanisms and Robotics, 16(6), 061013. https://doi.org/10.1115/1.4063406