Throwing objects with the superpropulsion effect

G. Giombini, C. D'Angelo, F. Celestini, C. Raufaste

Université Côte d'Azur, CNRS, Institut de Physique de Nice (INPHYNI),
06200 Nice, France
Institut Universitaire de France (IUF), 75005 Paris, France

A fascinating ability

- Throwing

  an action which consists in accelerating a projectile and then releasing it so that it follows a ballistic trajectory. (From Wikipedia)

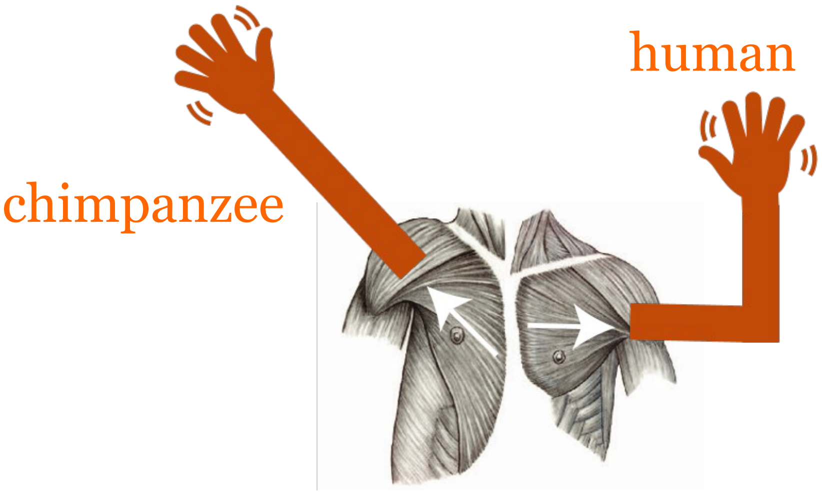
- Throw and records

  >12000 occurrences in Guinness World Records
  distance, speed, precision, frequency

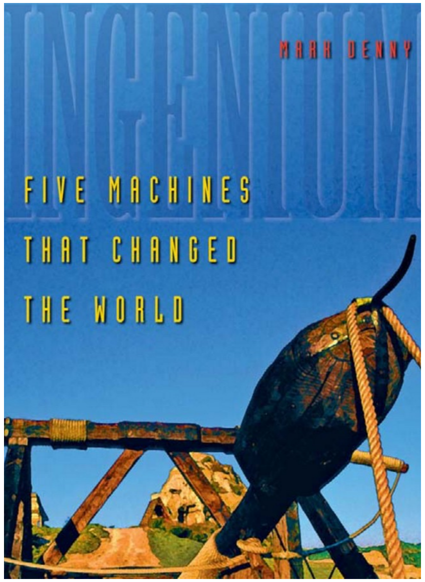
  “Longest throw of an object with no tail” (427.2 m)
  “Fastest Jai-Alai (Pelota) throw” (305.77 km/h)
  “Most basketball free throws in three minutes” (201)
  “Furthest distance to throw and catch an egg” (98.51 m)
  “Farthest throw of a washing machine” (4.45 m)
  “Most tea bags thrown into mugs in 30 seconds” (30)

Evolution of throwing in humans

- ☐ Humans
  - slow, weak, lack natural weapons
  - unique abilities among primates
  - hunting 2 Myr ago
- ☐ Anatomical features
  - rotation of the shoulder
  - elbow flexion
- ☐ Later development of tools/weapons
  - context: hunting, warfare, sports
  - spear - 0.5 Myr ago
  - bow - 70000 yr ago
  - counterweight trebuchet 900 yr ago



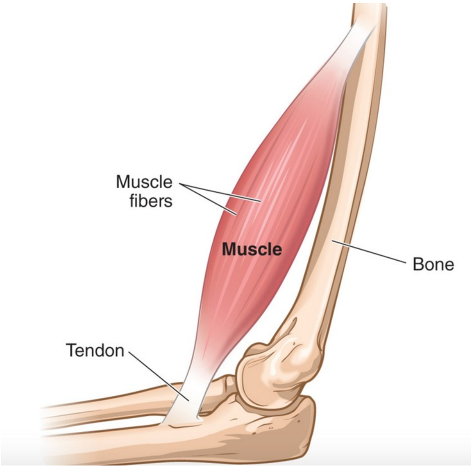
Roach et al., Nature (2013)


INGENIUM

MARK DENNY

FIVE MACHINES THAT CHANGED THE WORLD

Hand throwing



☐ Biomechanical aspects

sequential activation of many muscles

- legs, hips, torso, shoulder, elbow, wrist

role of tendons

- elastic energy storage and release
- accumulation and transmission of kinetic energy

☐ Available energy in shot putters

muscle power ~ 100 W/kg

muscle weight ~ 25 kg (20% of body mass)

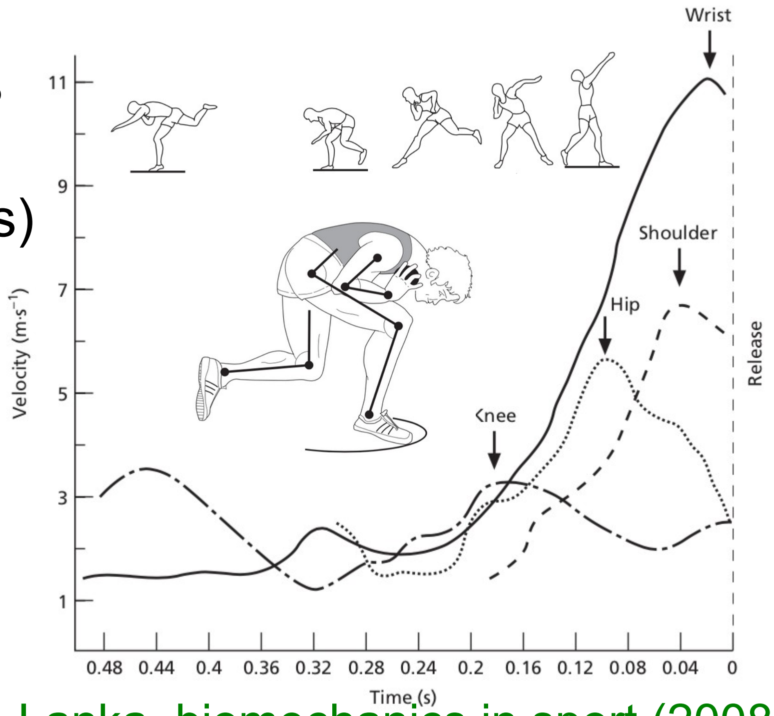
activation time ~ 200 ms

available energy ~ 500 J

☐ Kinetic energy of the shot

$v_{shot} \sim 10$ m/s, $m_{shot} \sim 10$ kg

$KE_{shot} = 1/2 m_{shot} v^2_{shot} \sim 500$ J

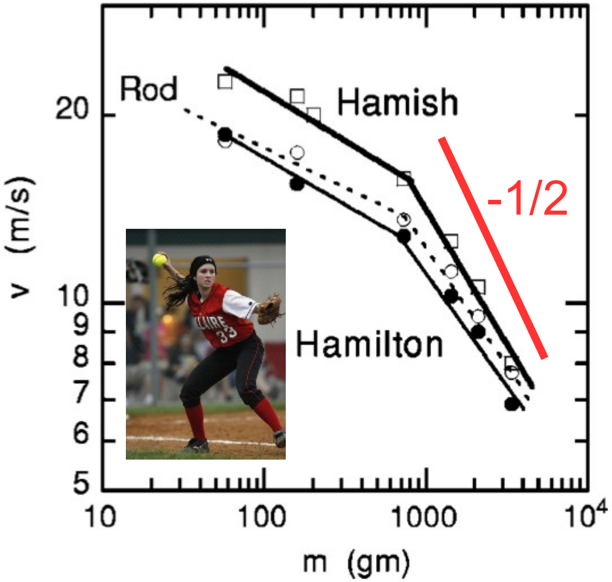


Lanka, biomechanics in sport (2008)

Always efficient ? A simple experiment

☐ Effect of the projectile mass

example in overarm throw
not efficient with light projectiles



Cross, Am. J. Phys. (2008)

☐ Simple model

kinetic energy
of the projectile

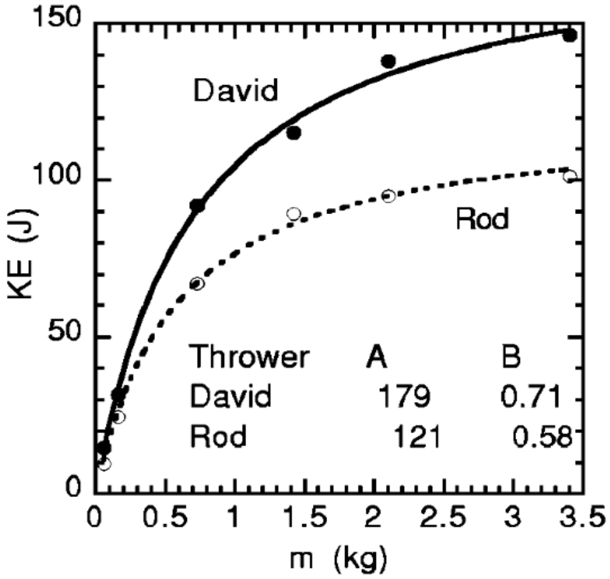
$$E_0 = KE = \frac{1}{2} m V^2 \text{ or } V = \sqrt{2E_0/m}$$

available energy
in muscles

Always efficient ? A simple experiment

☐ Effect of the projectile mass

example in overarm throw
not efficient with light projectiles



Cross, Am. J. Phys. (2008)

☐ Simple model

kinetic energy
of the projectile

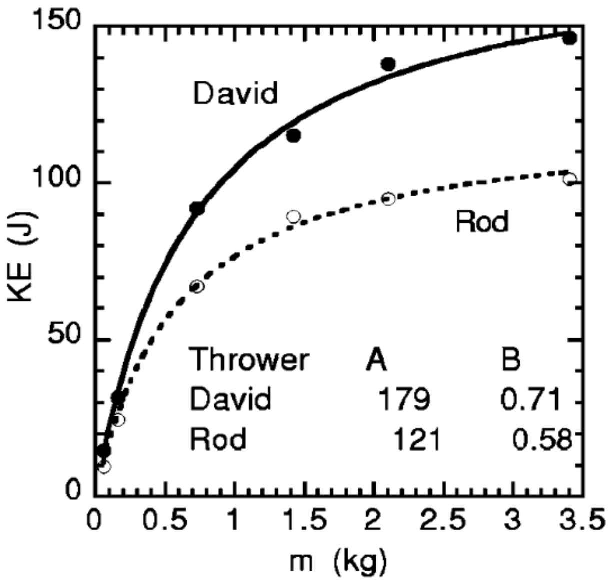
$$E_0 = KE = \frac{1}{2}mV^2 \text{ or } V = \sqrt{2E_0/m}$$

available energy
in muscles

Always efficient ? A simple experiment

☐ Effect of the projectile mass

example in overarm throw
not efficient with light projectiles



Cross, Am. J. Phys. (2008)

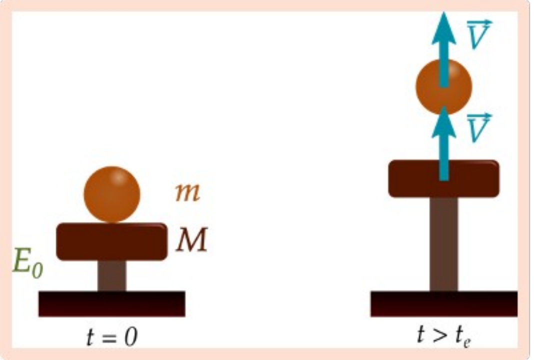
☐ Simple model

kinetic energy (KE)
of the projectile

$$E_0 = \frac{1}{2}mV^2 + \frac{1}{2}MV^2 \text{ or } KE = \frac{E_0}{1+M/m}$$

available energy
in muscles

kinetic energy remaining
in the body through the motion
of a virtual mass M



☐ Implications

$M \approx 2$ kg corresponds to hand and forearm
Difficulties to throw at large distances
Higher risk of injuries with light objects

Light projectiles: need for a tool

- Efficiency KE/E_0

Limit	Projectile	Handthrow $M \sim 2$ kg	Throw with instrument
$m \gg M$	shot put (~7.3 kg)	$KE/E_0 \sim 80$ %	-
$m \ll M$	basque pelota (~150 g)	$KE/E_0 \sim 7$ %	chistera $V \simeq 35$ m/s, $KE \simeq 150$ J $KE/E_0 \sim 30\text{-}35$ %

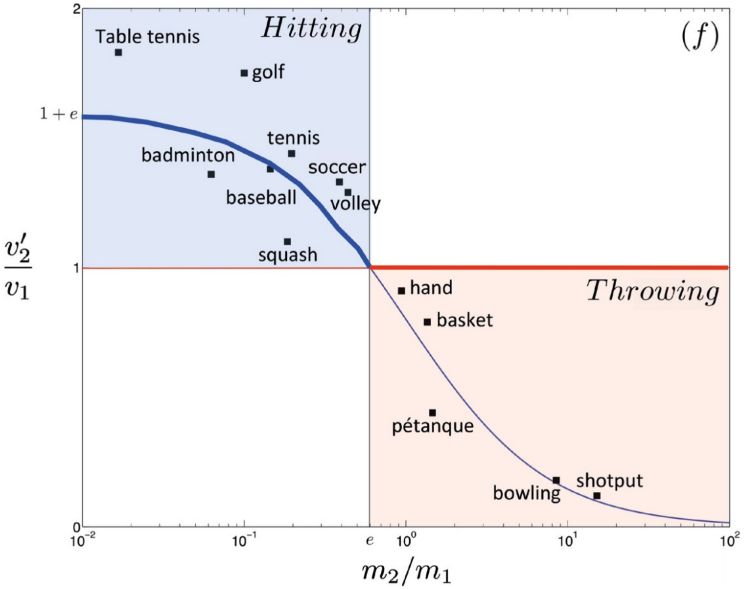
Light projectiles: need for a tool

☐ Efficiency KE/E_0

Limit	Projectile	Handthrow M ~ 2 kg	Throw with instrument
m≫M	shot put (~7.3 kg)	KE/E_0 ~ 80 %	-
m≪M	basque pelota (~150 g)	KE/E_0 ~ 7 %	chistera V≃35 m/s, KE≃150 J KE/E_0 ~ 30-35 %

☐ Other strategies with tools

hitting (golf, tennis, ...)
spinning (sling, hammer throw ...)
loading (bow, slingshot ...)



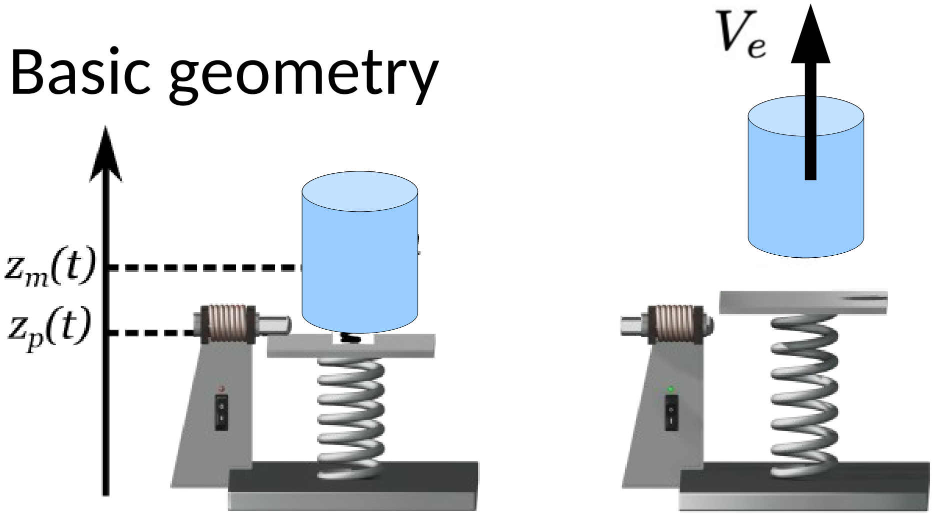
Cohen & Clanet, Europhys. News 2016

Scientific questions

- How to increase the throw efficiency of light objects ?
- Can we find other strategies than the use of a tool ?
  - Mimic the action of tendons
- What input from soft matter and materials physics ?
  - Find the good materials and geometries to reach relevant time scales

Main idea

- Basic geometry



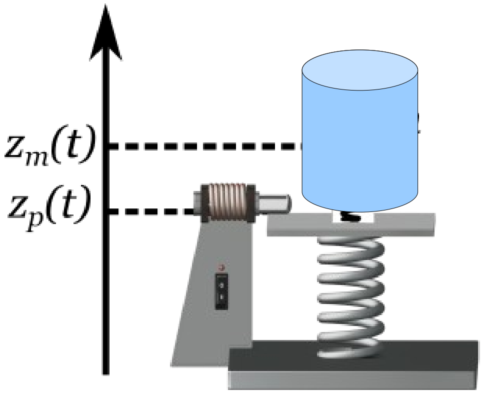
Perfect throwing engine (M>>m)
Harmonic motion
Amplitude *A*, frequency *f*

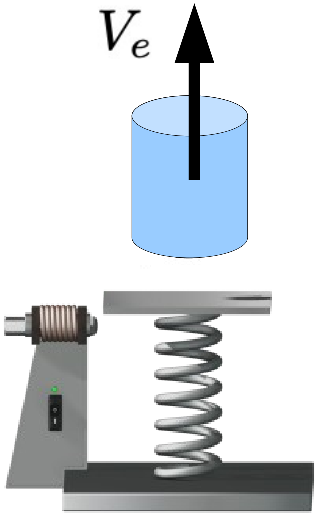
$$z_p(t) = A[1 - \cos(2\pi f t)]$$

$$V_p^* = 2\pi f A$$ maximum speed

Main idea

☐ Basic geometry





Perfect throwing engine (M>>m)
Harmonic motion
Amplitude A, frequency f

$$z_p(t) = A[1 - \cos(2\pi f t)]$$

$$V_p^* = 2\pi f A$$ maximum speed

☐ Case of a rigid object

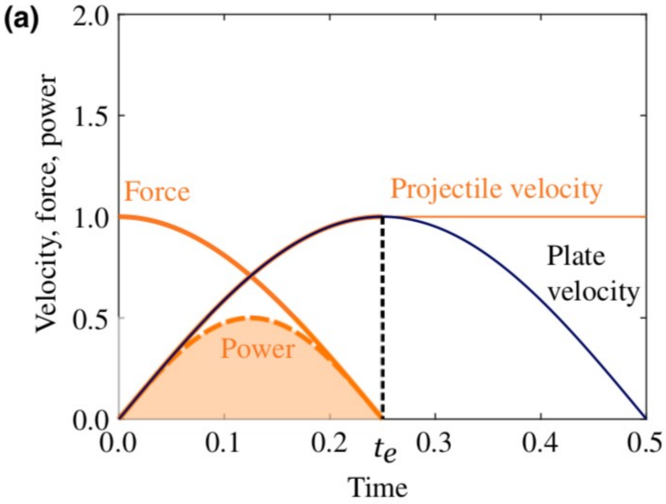
ejection speed

$$V_e = V_p^\star$$

transferred energy

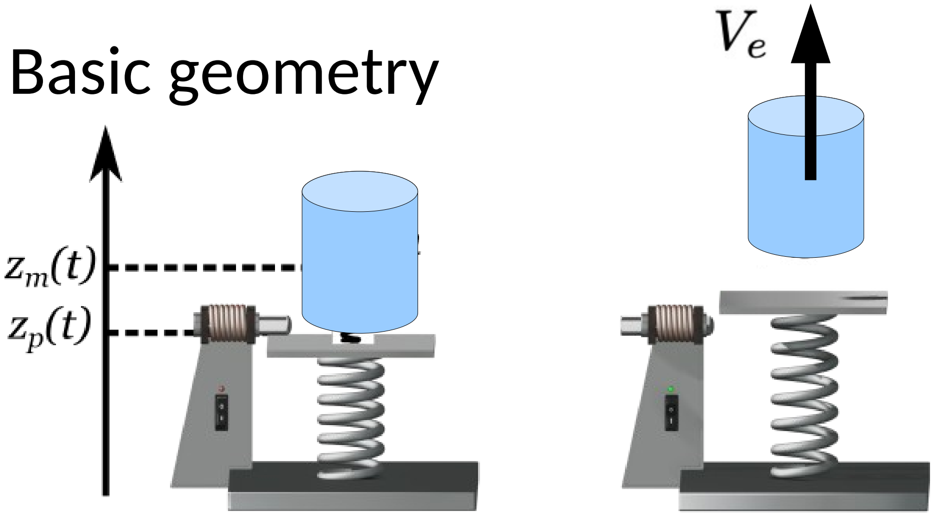
$$\int_0^{t_e} F(t)\dot{z}_p(t)dt$$

rigid object



Main idea

☐ Basic geometry



Perfect throwing engine (M>>m)
Harmonic motion
Amplitude A, frequency f

$$z_p(t) = A[1 - \cos(2\pi f t)]$$

$$V_p^* = 2\pi f A$$ maximum speed

☐ Case of a rigid object

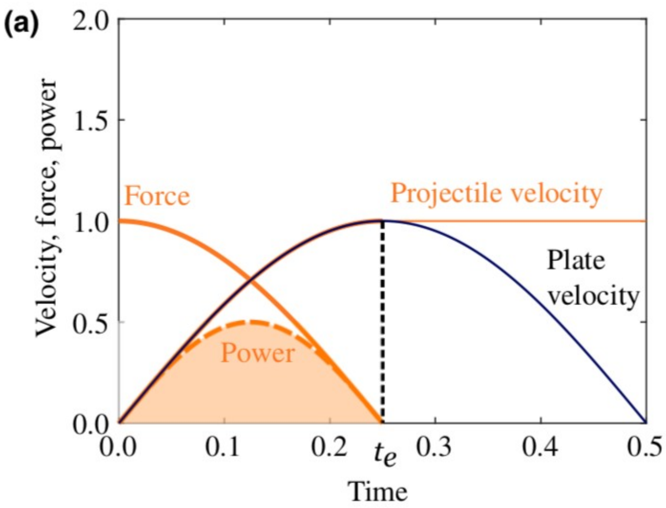
ejection speed

$$V_e = V_p^\star$$

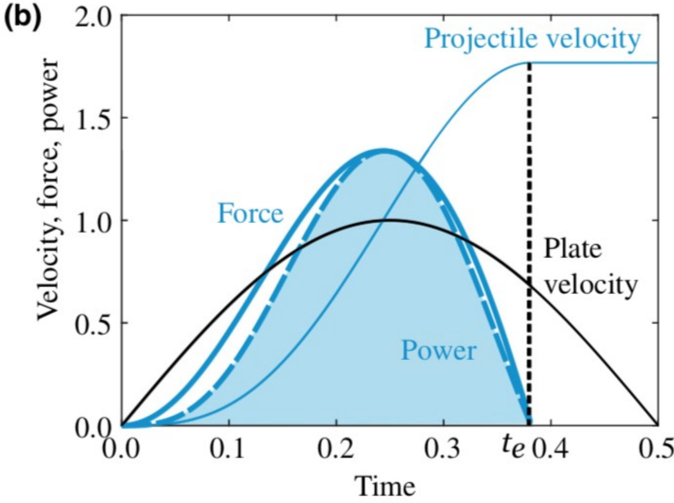
transferred energy

$$\int_0^{t_e} F(t)\dot{z}_p(t)dt$$

rigid object



optimal case
delayed force system



Solution: soft elastic projectiles

☐ Requirements

Delayed response and tunable time scale
Good elastic restitution

☐ Examples of quasi-1D gelatin hydrogels

Young modulus 12 kPa
Deformation wave speed c = 3.4 m/s
Typical length L: 3 - 30 mm
Eigenfrequency $f_0=c/(2L)$: 60 - 600 Hz

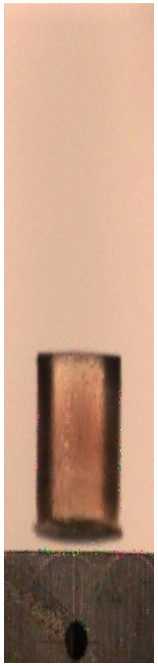
Solution: soft elastic projectiles

☐ Requirements

Delayed response and tunable time scale
Good elastic restitution

☐ Examples of quasi-1D gelatin hydrogels

Young modulus 12 kPa
Deformation wave speed c = 3.4 m/s
Typical length L: 3 - 30 mm
Eigenfrequency $f_0=c/(2L)$: 60 - 600 Hz



A~1 mm
f~50 Hz

Solution: soft elastic projectiles

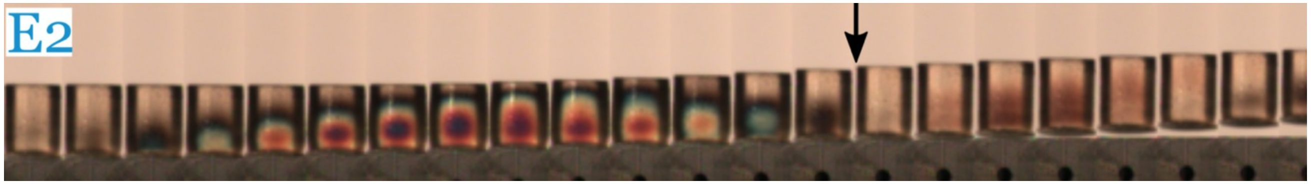
☐ Requirements

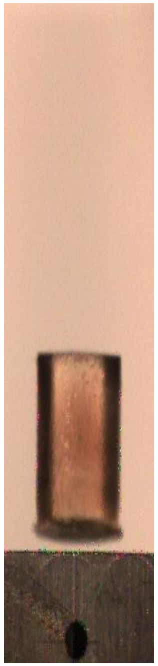
Delayed response and tunable time scale
Good elastic restitution

☐ Examples of quasi-1D gelatin hydrogels

Young modulus 12 kPa
Deformation wave speed c = 3.4 m/s
Typical length L: 3 - 30 mm
Eigenfrequency $f_0=c/(2L)$: 60 - 600 Hz

☐ Typical time sequence



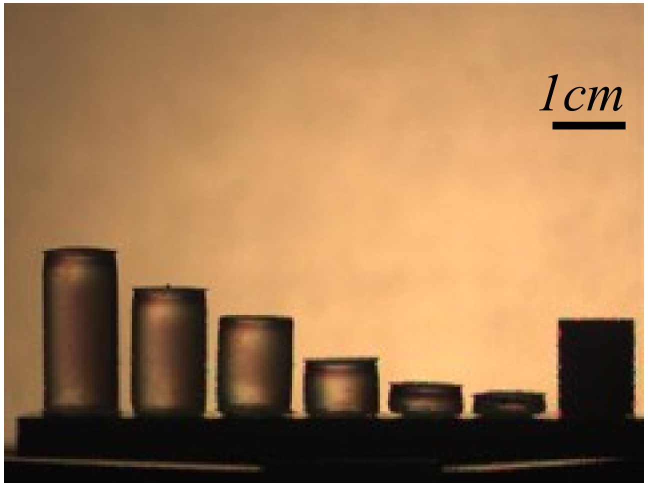


A~1 mm
f~50 Hz

Solution: soft elastic projectiles

☐ Results

Effect of the size for a given frequency *f*



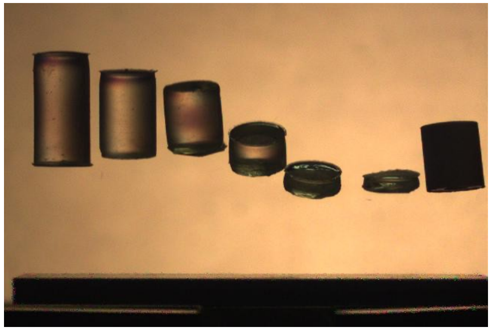
f~50 Hz

rigid

Solution: soft elastic projectiles

☐ Results

Effect of the size for a given frequency f



Solution: soft elastic projectiles

☐ Results

Effect of the size for a given frequency f

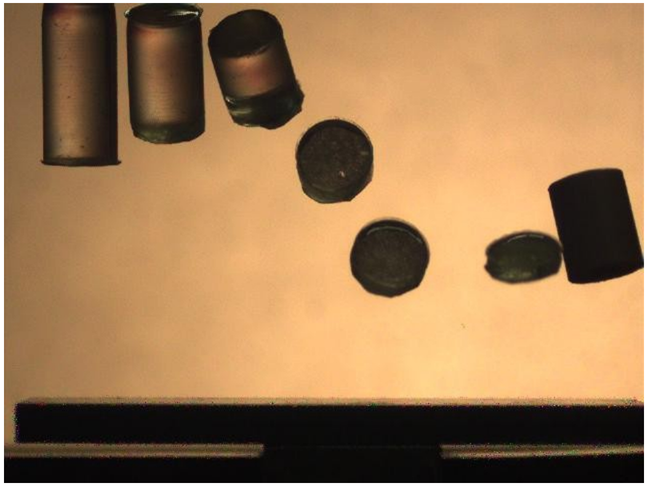
☐ Energy transfer factor

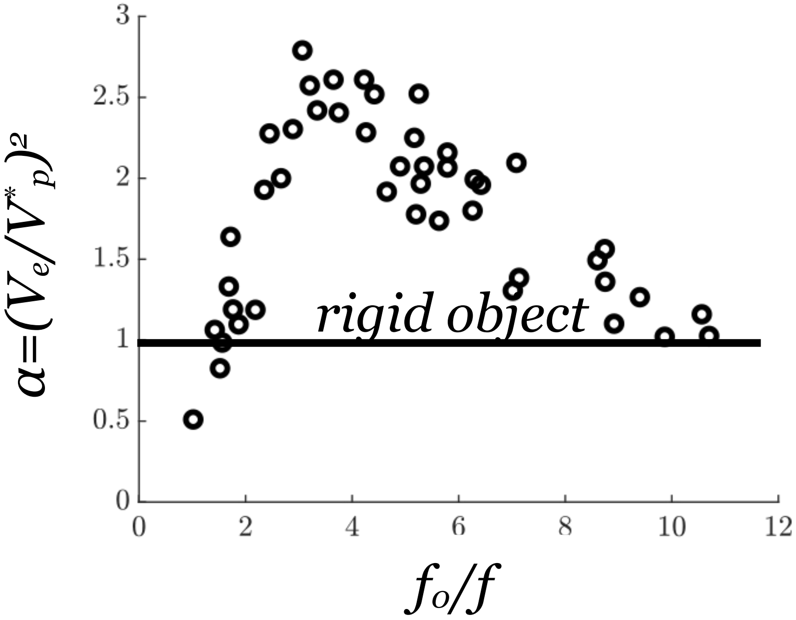
$\alpha=(V_e/V^*_p)^2$

Effect of the dimensionless frequency f_o/f

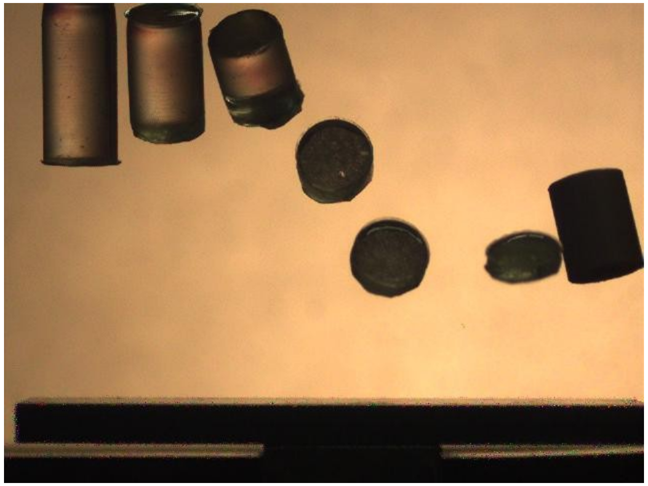
Optimal ratio $f_o/f \approx 3\text{-}4$ *gives* $\alpha \approx 2.5$

Specific resonance effect





Solution: soft elastic projectiles



☐ Results

Effect of the size for a given frequency f

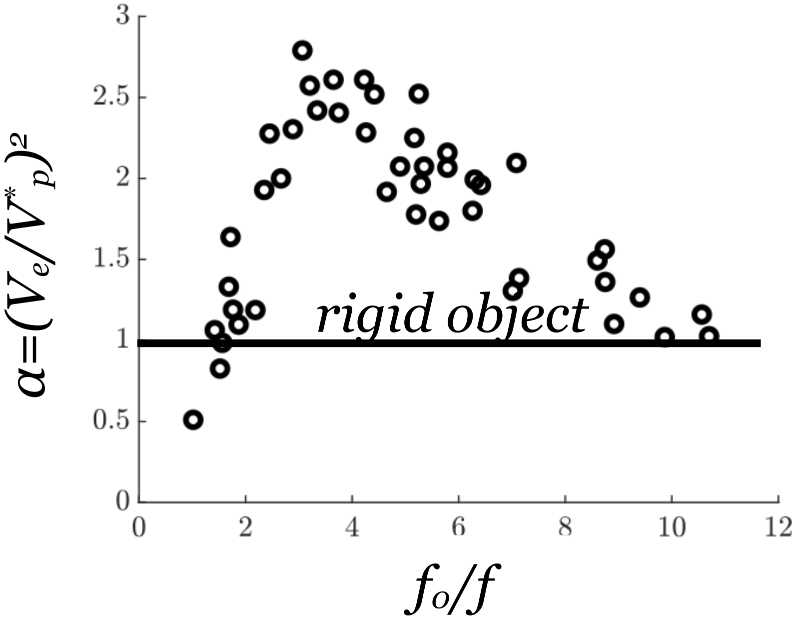
☐ Energy transfer factor

$\alpha=(V_e/V^*_p)^2$

Effect of the dimensionless frequency f_o/f

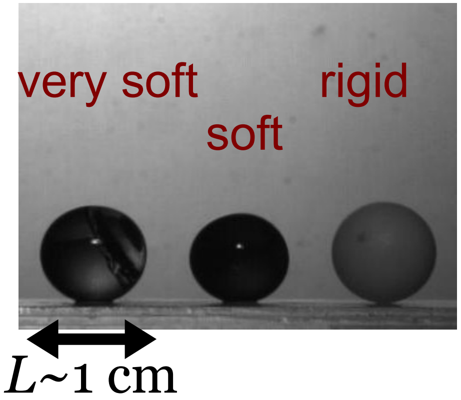
Optimal ratio $f_o/f \approx 3\text{-}4$ *gives* $\alpha \approx 2.5$

Specific resonance effect



☐ Other material/geometry

Polyacrylamide beads

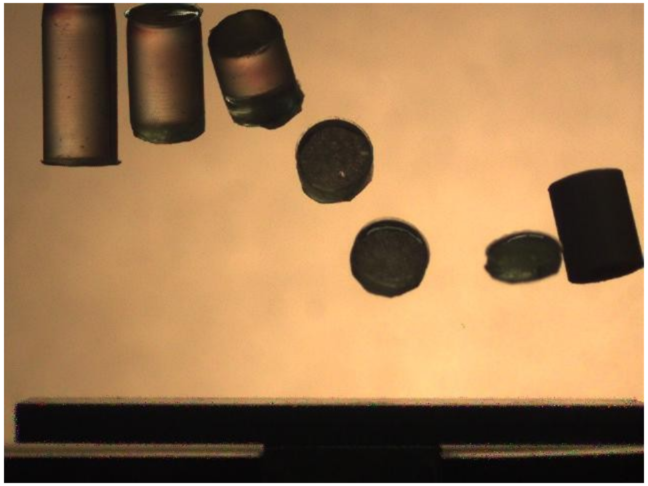


$$E \simeq 1 - 10 \text{ kPa}$$

$$f_0 \sim \frac{1}{L}\sqrt{\frac{E}{\rho}}$$

$$50 - 200 \text{ Hz}$$

Solution: soft elastic projectiles



☐ **Results**

Effect of the size for a given frequency f

☐ **Energy transfer factor**

$\alpha=(V_e/V^*_p)^2$

Effect of the dimensionless frequency f_o/f

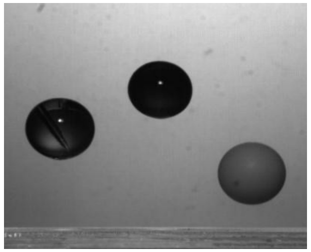
Optimal ratio $f_o/f\approx 3\text{-}4$ *gives* $\alpha\approx 2.5$

Specific resonance effect

☐ **Other material/geometry**

Polyacrylamide beads

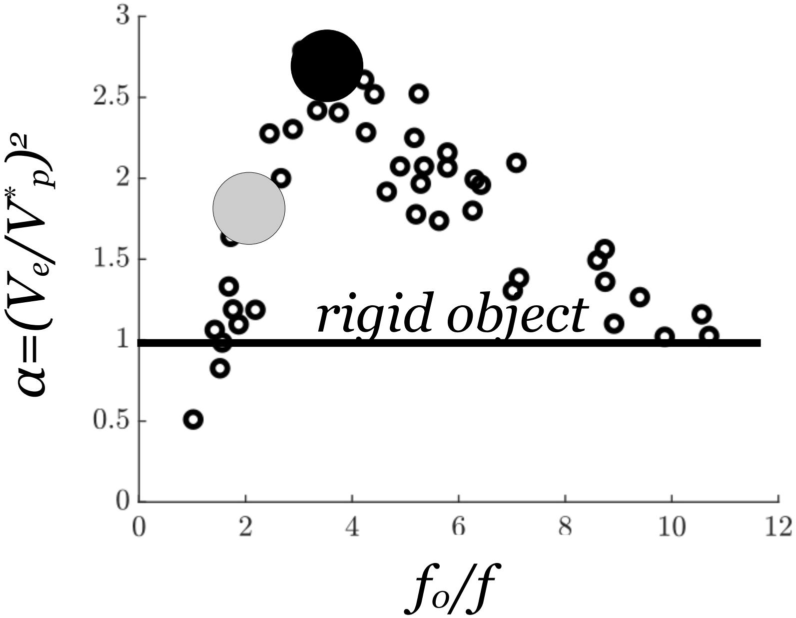
f~67 Hz



$$E \simeq 1-10\ \mathrm{kPa}$$

$$f_0 \sim \frac{1}{L}\sqrt{\frac{E}{\rho}}$$

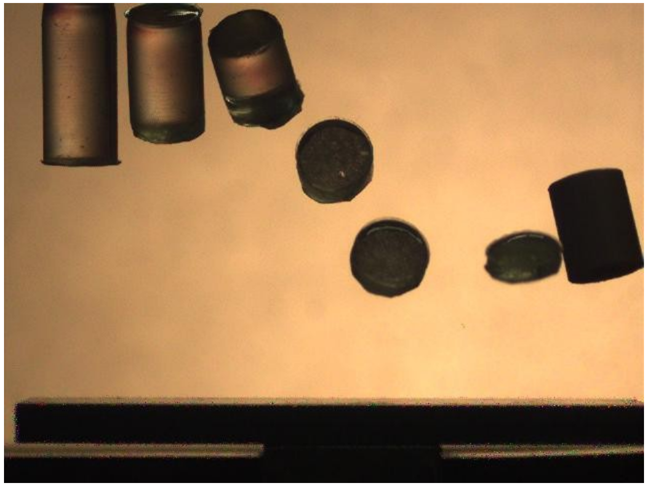
$$50-200\ \mathrm{Hz}$$



Solution: soft elastic projectiles

☐ Results

Effect of the size for a given frequency f



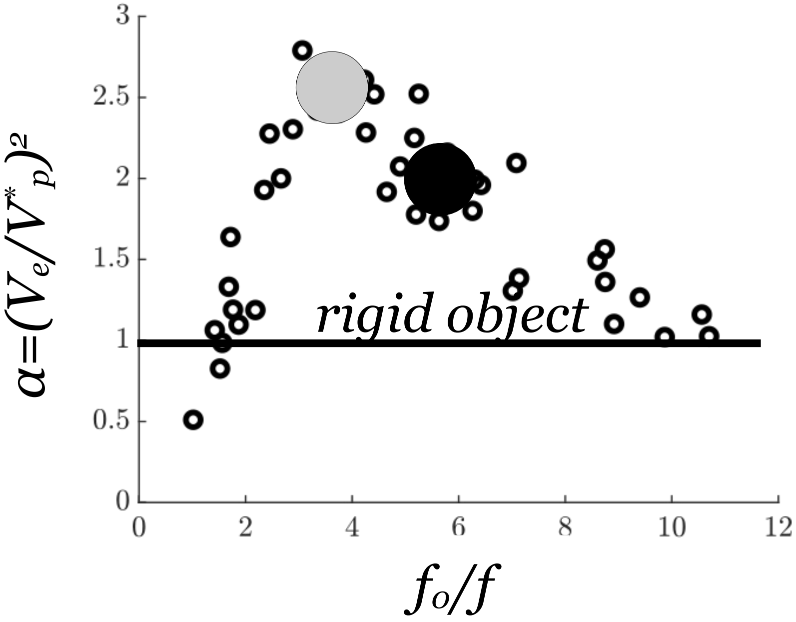
☐ Energy transfer factor

$\alpha=(V_e/V^*_p)^2$

Effect of the dimensionless frequency f_o/f

Optimal ratio f_o/f *≈3-4 gives* α*≈2.5*

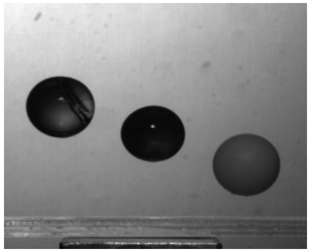
Specific resonance effect



☐ Other material/geometry

Polyacrylamide beads

f~26 Hz



$$E \simeq 1 - 10 \text{ kPa}$$

$$f_0 \sim \frac{1}{L}\sqrt{\frac{E}{\rho}}$$

$$50 - 200 \text{ Hz}$$

Solution: soft elastic projectiles

☐ General mechanism: superpropulsion

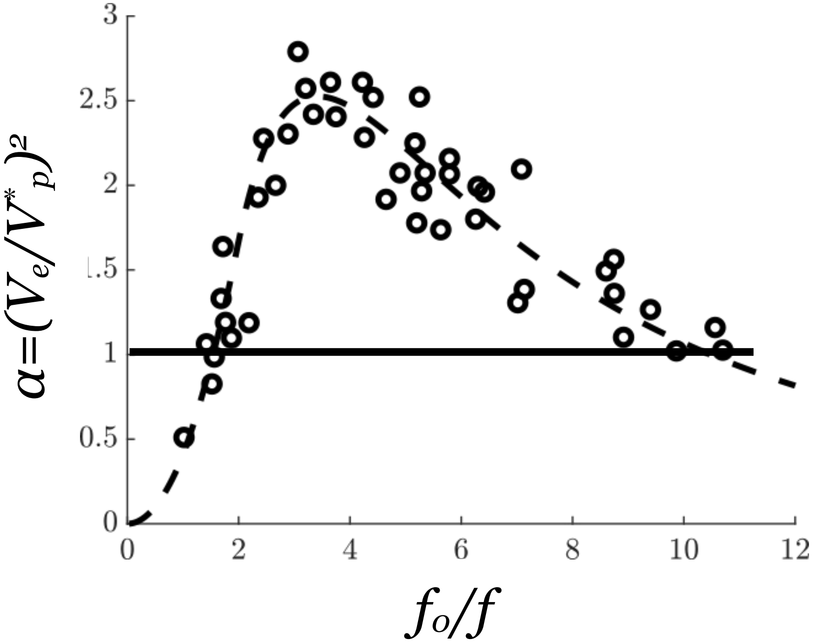
Matching deformation/throw dynamics

Optimal value of the parameter $f_o/f \approx 3\text{-}4$

Gain in kinetic energy $\alpha \approx 2.4\text{-}2.7$

☐ Perfect agreement with models

$f_o/f = 3.4$ and $\alpha = 2.5$



Application 1: droplet ejection

☐ Droplet dynamics

Deformation associated with surface tension

Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$

Application 1: droplet ejection

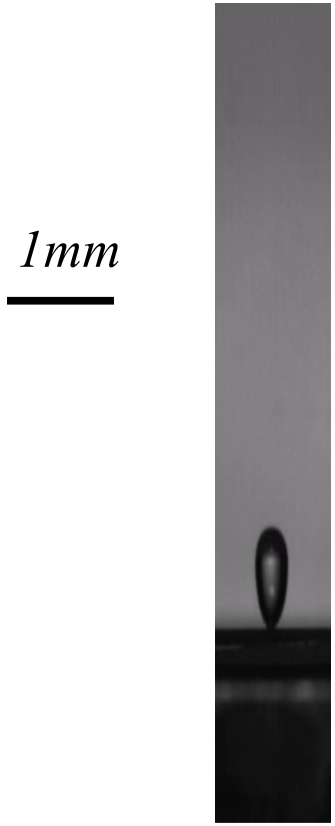
☐ Droplet dynamics

Deformation associated with surface tension
Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$

☐ Parameters

drop radius R ~ 1mm, f_o ~ 300Hz
catapult amplitude A ~ 1-10mm
catapult frequency f ~ 20-100Hz
catapult acceleration ~ 10g
ejection velocity V_e ~1m/s



adhesionless substrates
collaboration with chemists
f=37Hz A=1.4mm

Application 1: droplet ejection

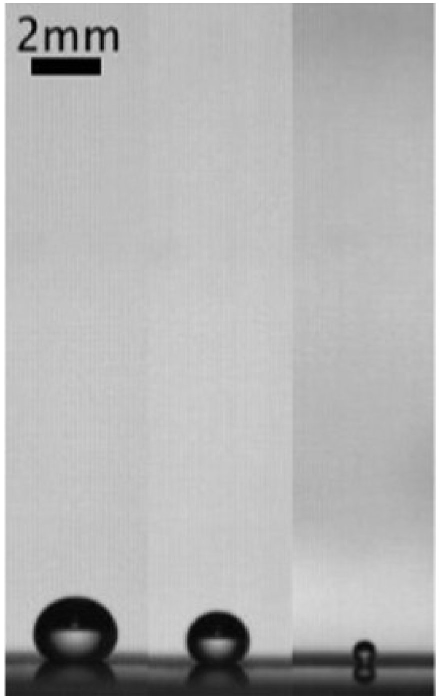
☐ Droplet dynamics

Deformation associated with surface tension
Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$

☐ Parameters

drop radius R ~ 1mm, f_o ~ 300Hz
catapult amplitude A ~ 1-10mm
catapult frequency f ~ 20-100Hz
catapult acceleration ~ 10g
ejection velocity V_e ~1m/s



adhesionless substrates
collaboration with chemists
f=37Hz A=1.4mm

Application 1: droplet ejection

☐ Droplet dynamics

Deformation associated with surface tension

Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$

☐ Parameters

drop radius R ~ 1mm, f_o ~ 300Hz

catapult amplitude A ~ 1-10mm

catapult frequency f ~ 20-100Hz

catapult acceleration ~ 10g

ejection velocity V_e ~1m/s

adhesionless substrates

collaboration with chemists

f=37Hz A=1.4mm

Application 1: droplet ejection

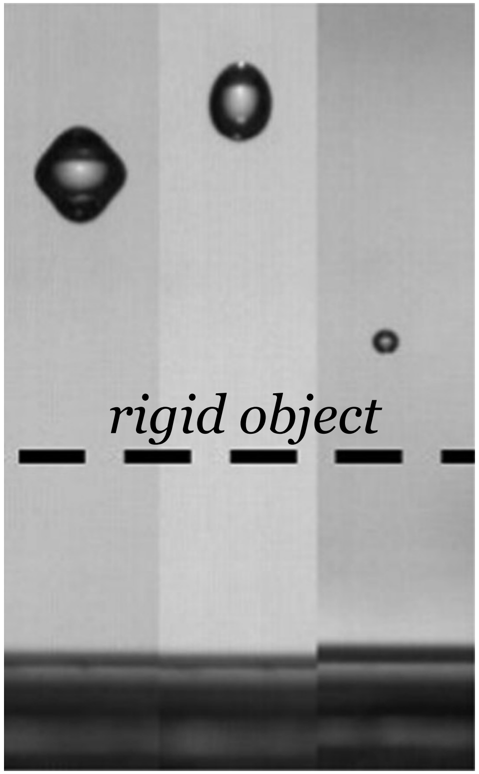
☐ Droplet dynamics

Deformation associated with surface tension
Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$

☐ Parameters

drop radius R ~ 1mm, f_o ~ 300Hz
catapult amplitude A ~ 1-10mm
catapult frequency f ~ 20-100Hz
catapult acceleration ~ 10g
ejection velocity V_e ~1m/s



adhesionless substrates
collaboration with chemists
f=37Hz A=1.4mm

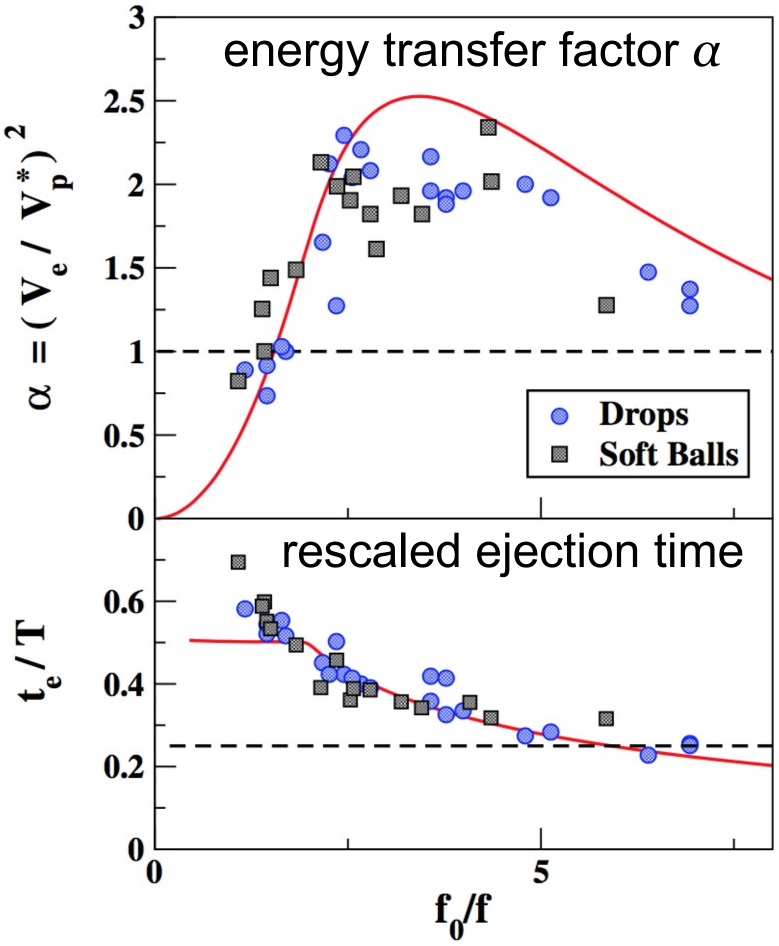
Application 1: droplet ejection

☐ Droplet dynamics

Deformation associated with surface tension

Eigenfrequency

$$f_0 \sim \sqrt{\frac{\gamma}{\rho R^3}}$$



☐ Parameters

drop radius R ~ 1mm, f_o ~ 300Hz
catapult amplitude A ~ 1-10mm
catapult frequency f ~ 20-100Hz
catapult acceleration ~ 10g
ejection velocity V_e ~1m/s

Application 1: droplet ejection

☐ Applications

Droplet actuation and sorting
Energy saving
Already present in nature !

Application 1: droplet ejection

- ☐ Applications
  - Droplet actuation and sorting
  - Energy saving
  - Already present in nature !

Droplet superpropulsion in an energetically constrained insect
Sharpshooters need to evacuate 300x their mass in urine everyday !
Challita et al., Nature Com. 2023

Application 1: droplet ejection

☐ Applications

Droplet actuation and sorting
Energy saving
Already present in nature !

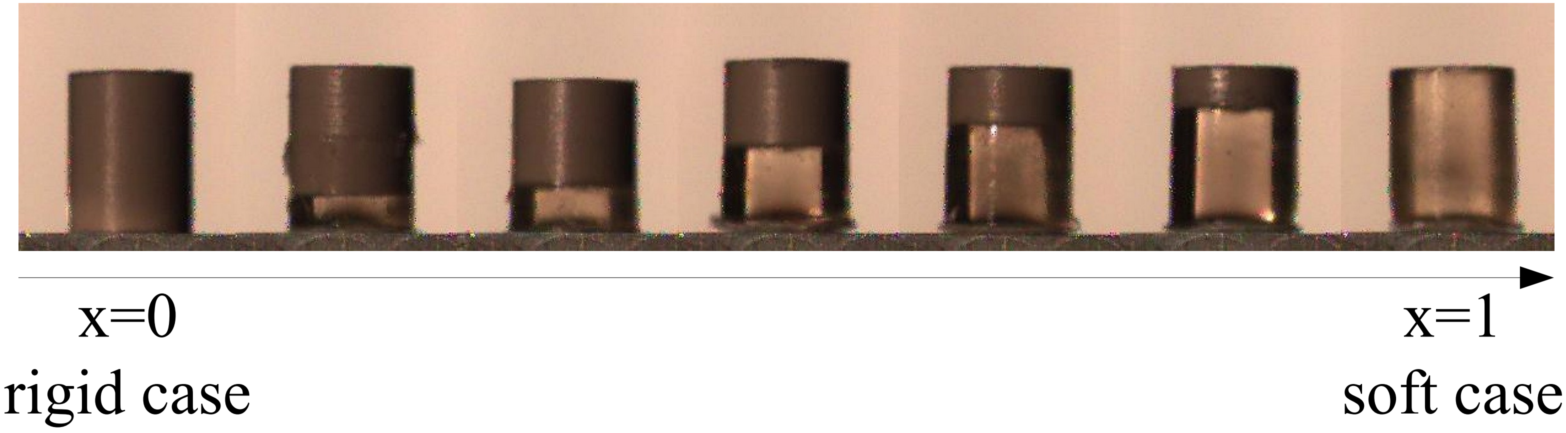
Droplet superpropulsion in an energetically constrained insect
Sharpshooters need to evacuate 300x their mass in urine everyday !
Challita et al., Nature Com. 2023

Application 2: boosting rigid projectiles

Application 2: boosting rigid projectiles

☐ Idea

Add a layer of soft elastic material at the bottom of rigid objects

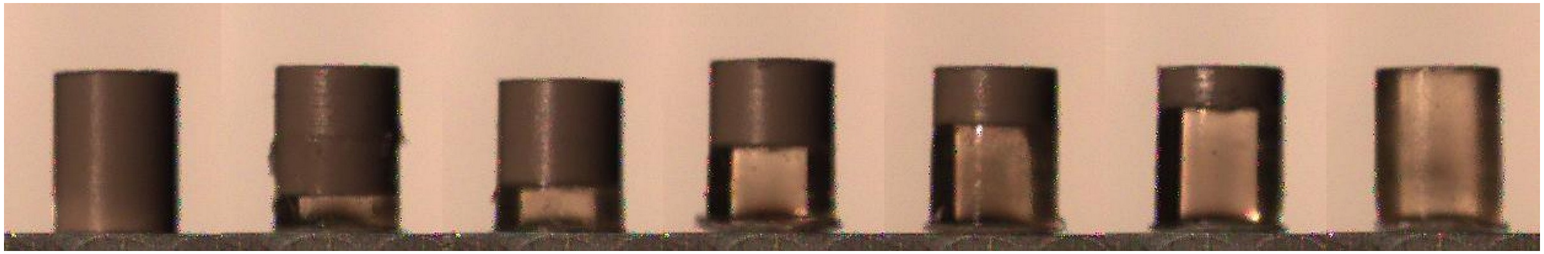


☐ Relevant parameters $f_o/f \rightarrow c_s/Lf$ and x

Application 2: boosting rigid projectiles

☐ Idea

Add a layer of soft elastic material at the bottom of rigid objects



$x=0$ → $x=1$

rigid case — soft case

☐ Relevant parameters $f_o/f \;\rightarrow\; c_s/Lf$ and x

$c_s/Lf=6.5$

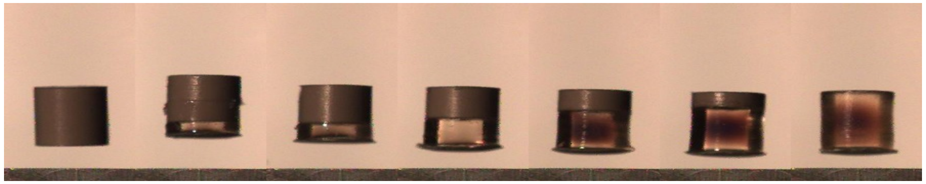
Application 2: boosting rigid projectiles

☐ Idea

Add a layer of soft elastic material at the bottom of rigid objects

☐ Relevant parameters $f_o/f \rightarrow c_s/Lf$ and x

$c_s/Lf=2.9$

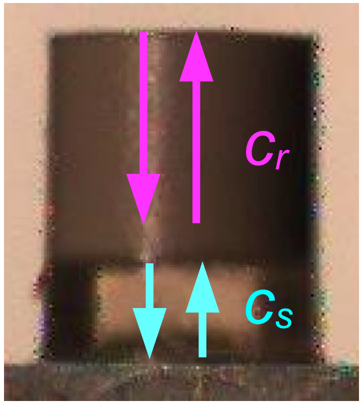


Application 2: boosting rigid projectiles

- ☐ Numerical approach

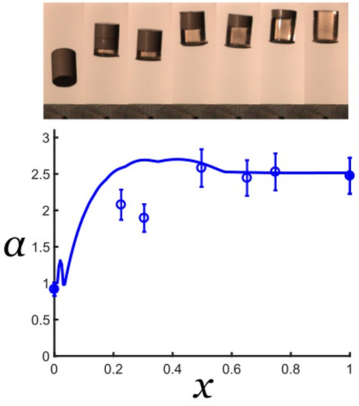
  1D wave equation in both layers ($c_r >> c_s$)

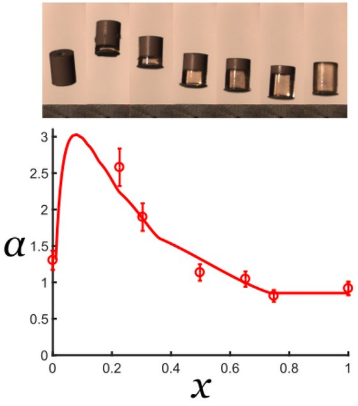
  right boundary conditions



Application 2: boosting rigid projectiles

- Numerical approach
  - 1D wave equation in both layers ($c_r >> c_s$)
  - right boundary conditions





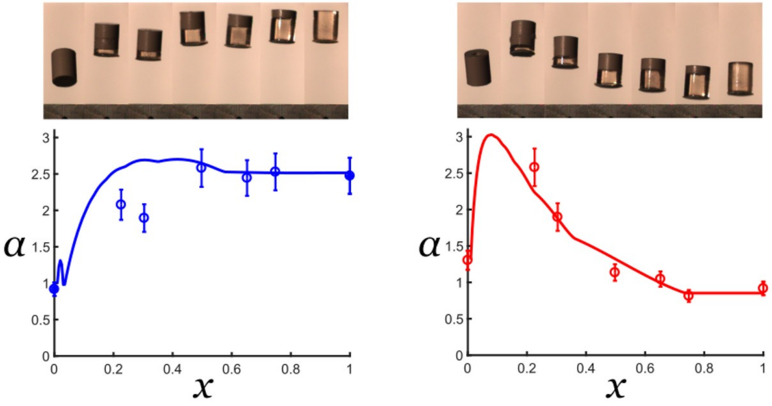
Application 2: boosting rigid projectiles

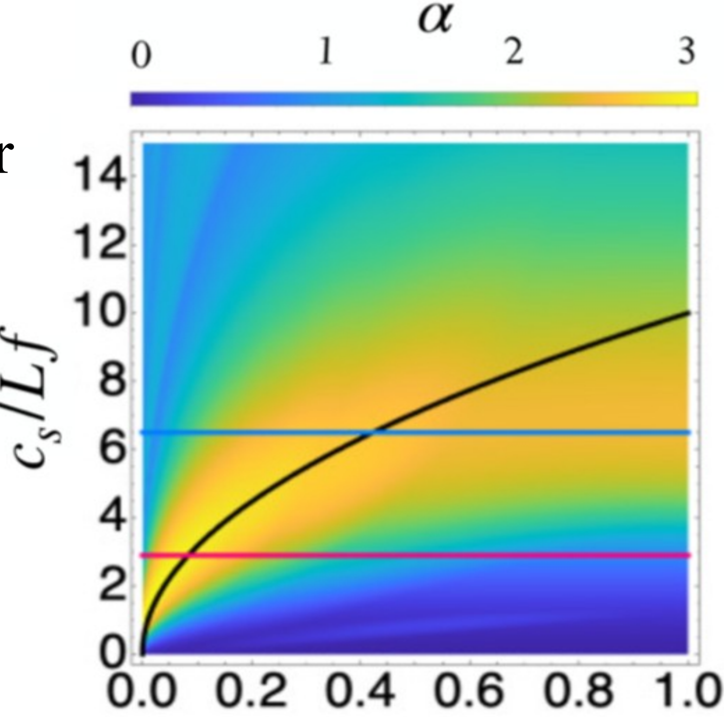
☐ Numerical approach

1D wave equation in both layers ($c_r >> c_s$)
right boundary conditions

☐ Results

Superpropulsion whatever x
Optimal crest





soft layer

very soft layer

100% rigid x 100% soft

Application 2: boosting rigid projectiles

☐ Numerical approach

1D wave equation in both layers ($c_r >> c_s$)
right boundary conditions

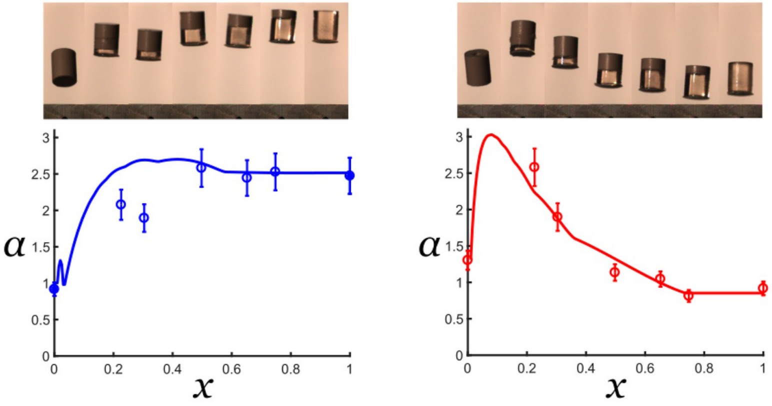
☐ Results

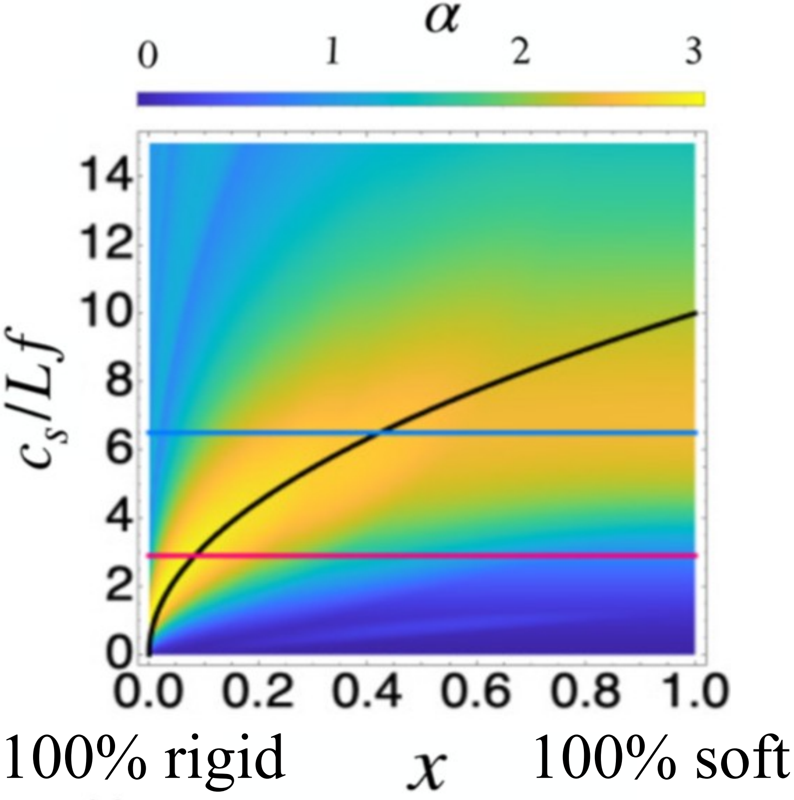
Superpropulsion whatever x
Optimal crest

☐ Two limits

$x \rightarrow 1$, α_{max}=2.5
wave dynamics inside the soft layer
fo/f = 3.4 for the optimal case

$x \rightarrow 0$, α_{max}=3
mass-spring system
fo/f = 1.6 for the optimal case





Conclusion

☐ General mechanism: superpropulsion

Matching deformation/throw dynamics

Specific resonance (physics and model dependent)

  optimal value of the parameter f_o/f

Different systems – same effect:

  waves, mass-spring system, surface tension, ...

☐ Input from soft matter and materials physics

Tunable properties, low elastic modulii

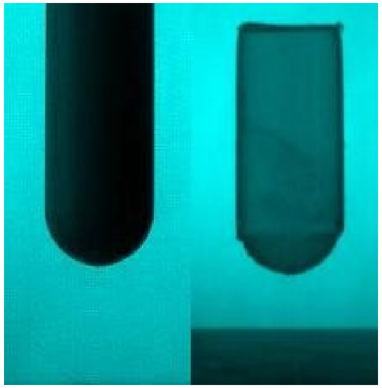
Typical acceleration time around 10-100 ms … can be extended !

☐ Applications in throws

250-300% gain in kinetic energy for light objects

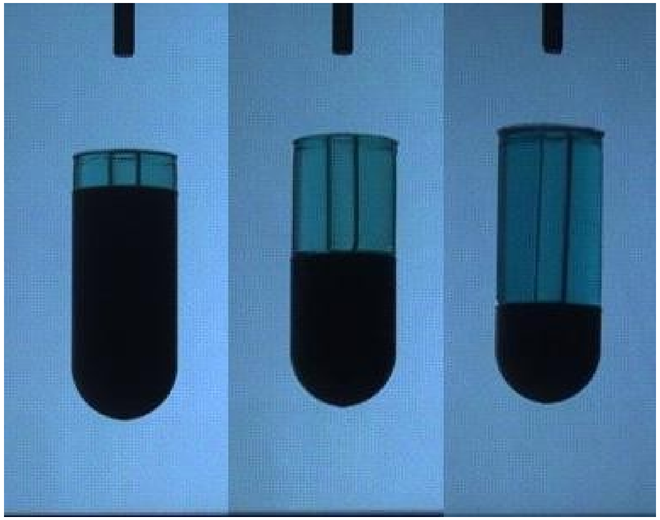
Related works

☐ Impact of bilayered projectiles



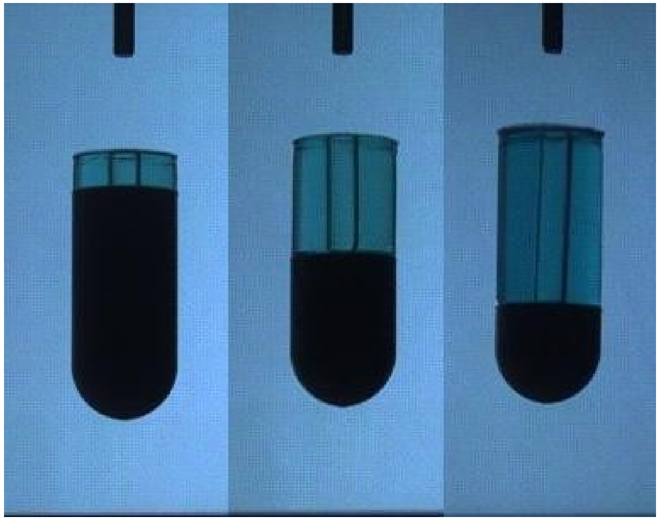
100% rigid
hard plastic

100% soft
gelatin hydrogel



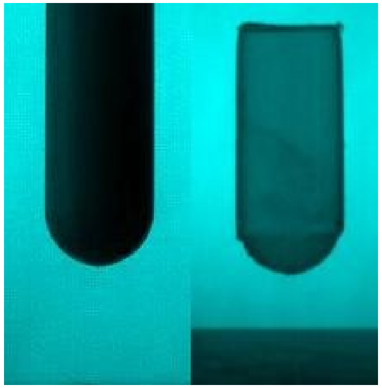
Related works

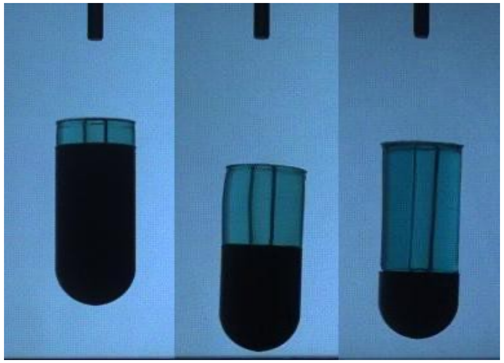
- Impact of bilayered projectiles



Related works

- Impact of bilayered projectiles





Acknowledgments

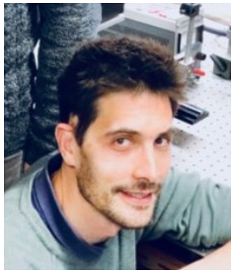
☐ Investigators at the physics institute of Nice


Franck
Celestini


Christophe
d'Angelo


Guillaume
Giombini


Médéric
Argentina


Cyrille
Claudet

☐ Collaborators and sponsors


Joachim Mathiesen
Niels Bohr Institute
Copenhagen


Laurence Viennot
MSC
Paris

UNIVERSITÉ CÔTE D'AZUR

cnrs

INPHYNI

IUF institut universitaire de France

AGENCE INNOVATION DÉFENSE