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Problem 4

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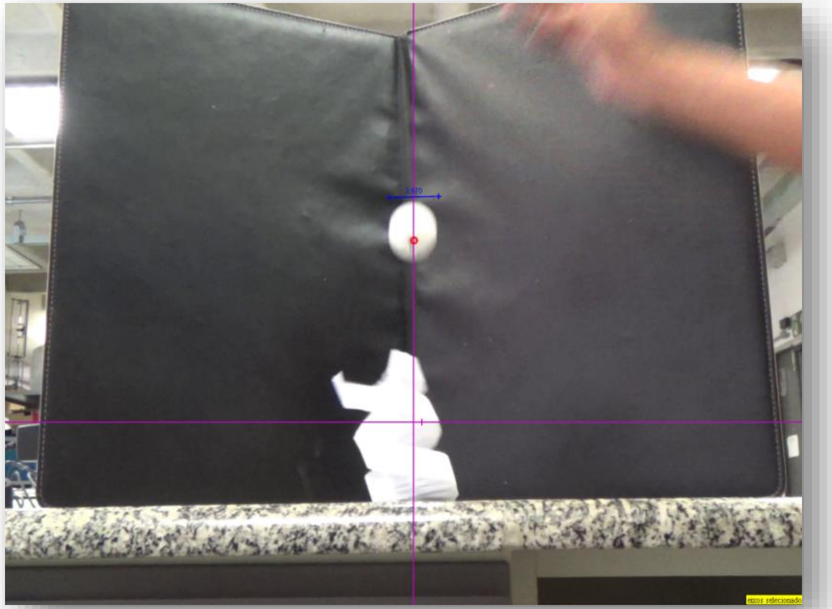
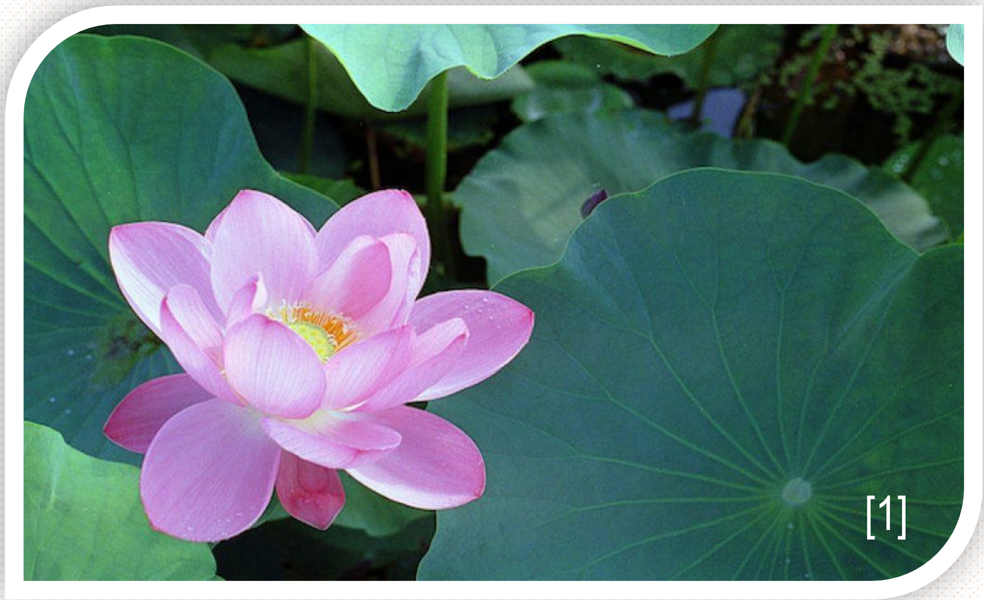
❑ The problem

- Folded paper structures such as the Miura-ori origami can be programmed to exhibit a wide range of **elastic properties** depending on their **crease and defect patterns**. Design and build an origami cannon to vertically launch a standard Ping-Pong ball using only a **single uncut sheet of A4 paper (80g/m²).** How is the height of the ball elevation related to the folding pattern? **Optimize your design to achieve the maximum height possible.**



❑ Metamaterials

- Origami metamaterials display, for example, auxetic behavior and multistability, the latter allowing reprogrammable configurations [3].



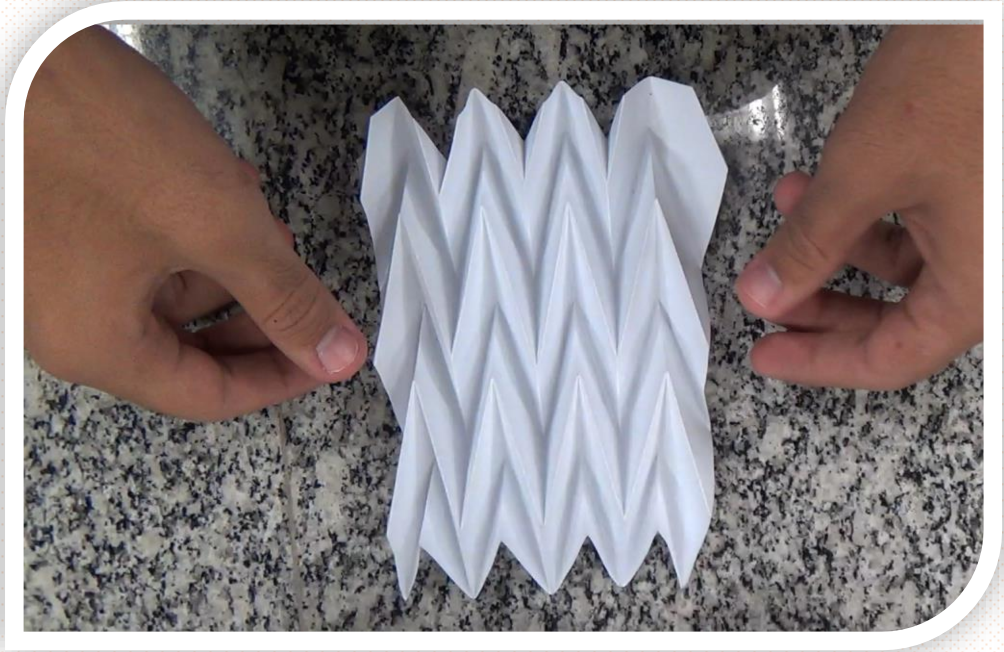
1. Flower petals

2. Insect wings

Images: 1. https://www.dreamstime.com/stock-photo-wings-insect-isolated-white-background-clipping-path-image72794552
2. https://www.asianscientist.com/2014/10/in-the-lab/making-3d-metamaterials-natural-bent/
3. PRL 2016, V. Brunck, **Elastic theory of origami-based metamaterials**

❑ Behavior of metamaterials

- Contraction and dilation of the system
- Movement in a given direction is reflected towards **another** direction



3. Configurable metamaterial

Image: https://materia.nl/article/toolkit-build-reconfigurable-metamaterials/

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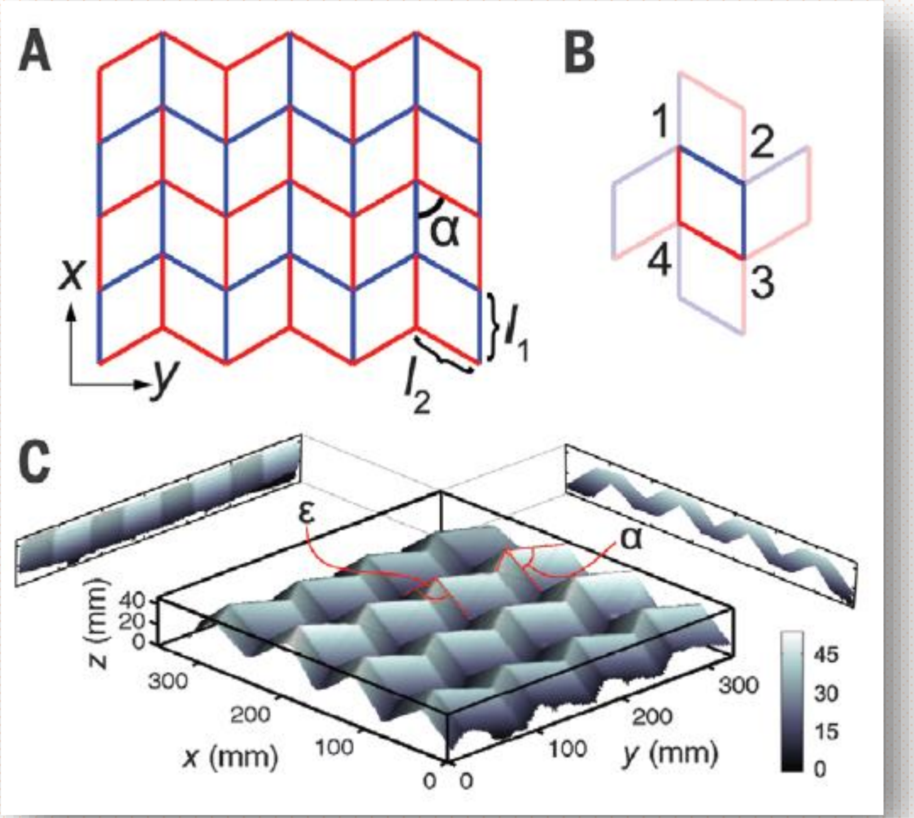
❑ Investigating Miura-Ori patterns



4. 3D reconstruction of Miura-Ori Patterns with geometric parameters

- Geometrical construction
- Based on creases and valleys
  - Can be characterized accordingly to different geometric angles and properties
- Very important: **Poisson's ration**!

Image: **Jesse L. Siverberg - "Using origami design principles to fold reprogrammable mechanical metamaterials"**

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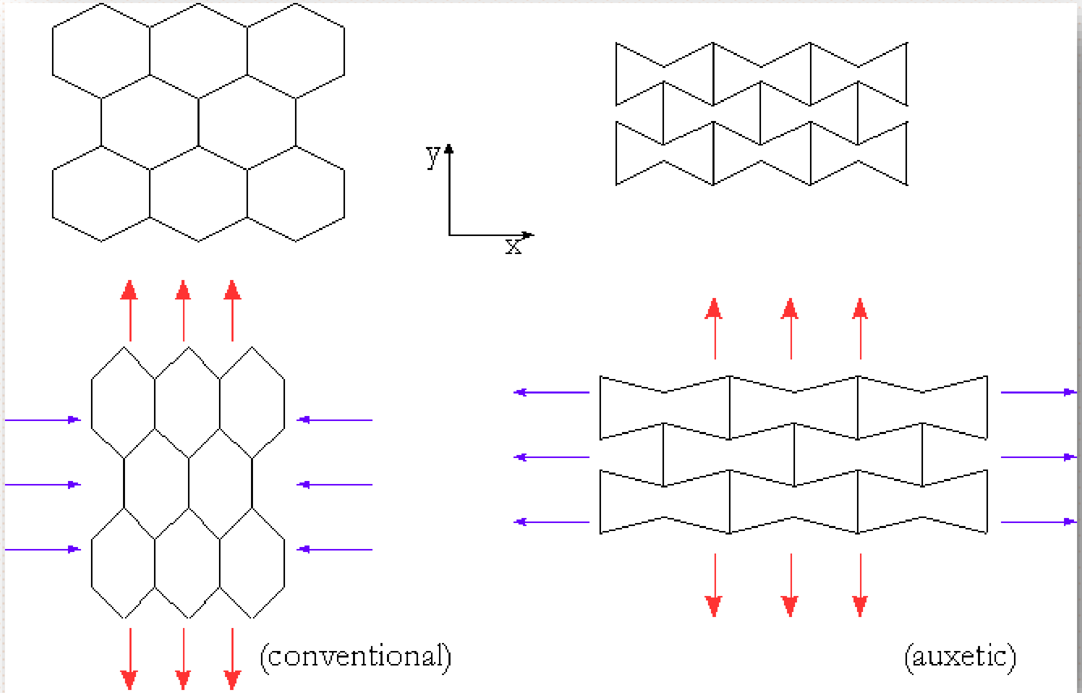
❑ Poisson's ratio- Why it is important

Equations

$v = Poisson's\ ratio$
$W = change\ in\ width$
$L = change\ in\ length$

- From the references [1], we have that the origami's Poisson's ratio is negative!
- Therefore, it is an auxetic material

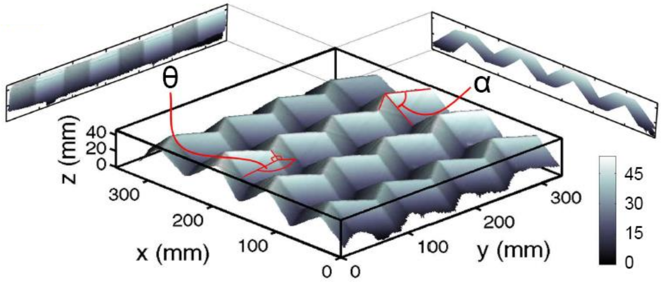
$$v = -\frac{W}{L}\frac{dL}{dW}$$ General case



5. Behavior of an auxetic material

Theoretical prediction for Miura-Ori

$$\boldsymbol{v = 1 - \frac{1}{sen\,\alpha\, sen\frac{\theta}{2}}}$$



6. 3D modelling for Miura-Ori pattern

Reference [1], Image 6- **Z.Y. Wei-** "Geometric Mechanics of Periodic Pleated Origami"
Image 5- https://groups.exeter.ac.uk/auxetic/auxetic_f2.html

❑ Negative Poisson's ratio- evidence

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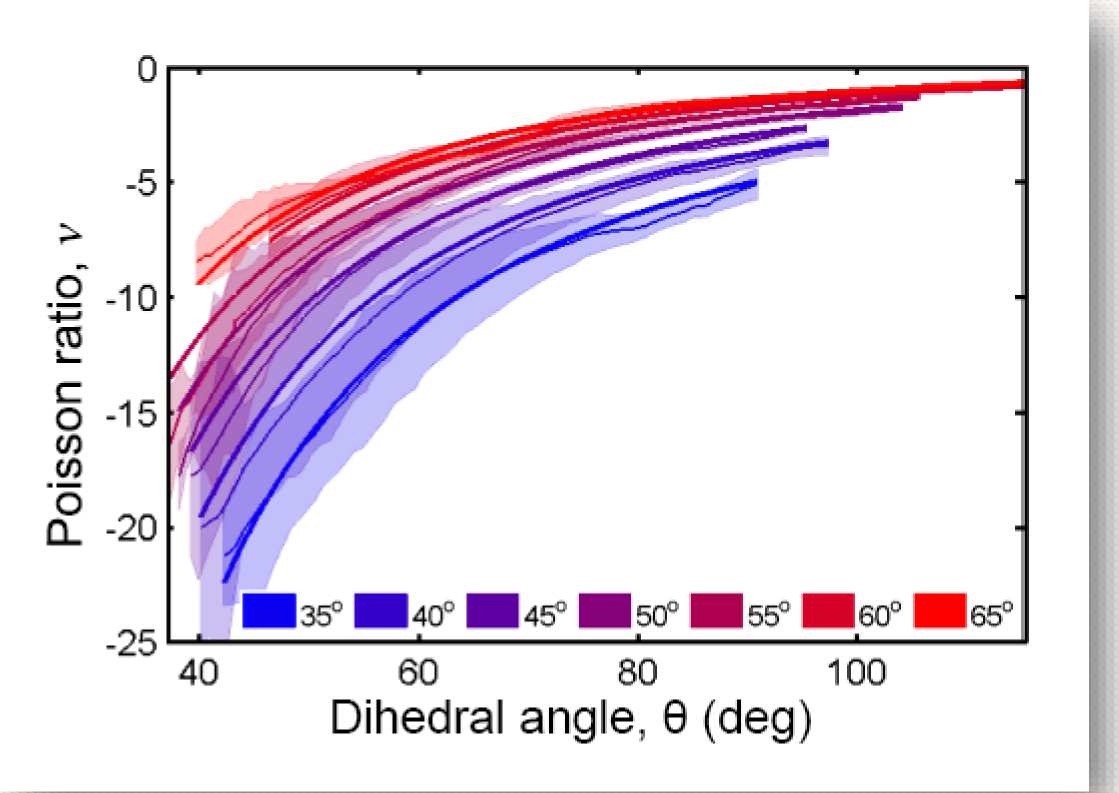

7. Experiments for Miura-Ori patterns confirming the negative Poisson's ratio.

- Justifies the choosing of a Miura-Ori pattern for our investigations
- Now focusing **on the problem** itself

Achieving maximum heights with a Miura-Ori

Image 7: **Jesse L. Siverberg - "Using origami design principles to fold reprogrammable mechanical metamaterials"**

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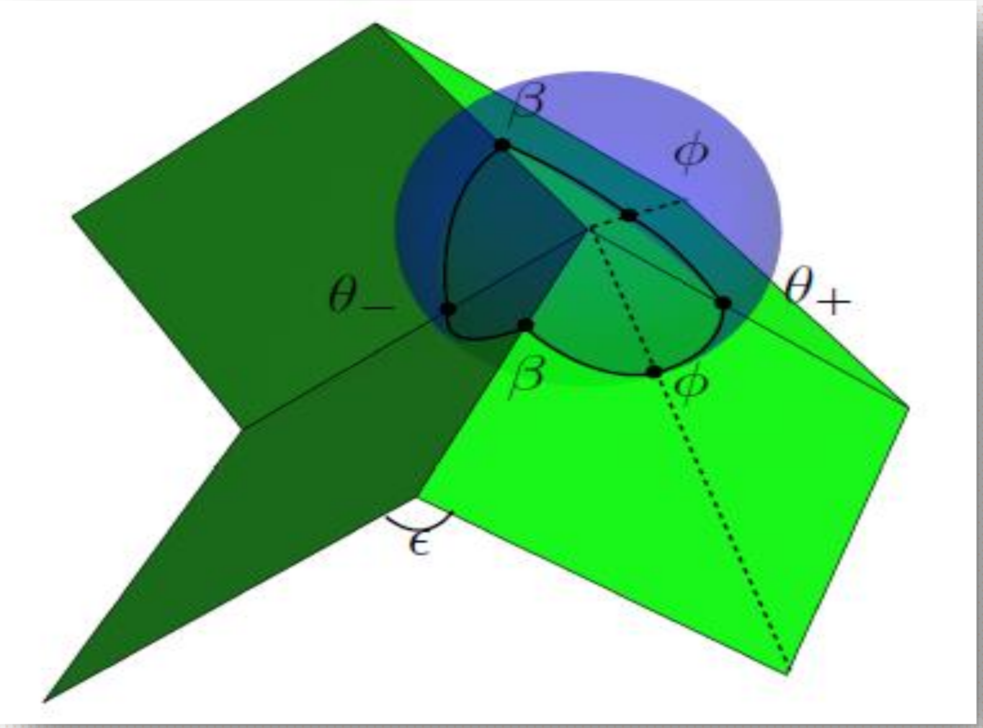
❑ Energy on a Miura-Ori origami

Equations

$l = fold\ lenght$
$k_0 = spring\ constant$



8. Angular schemes for a Miura-Ori folding pattern

Our model also considers pattern deffects!

Applied Angular Hooke's law

$$\frac{U}{k_0 l} = \frac{1}{2}(\theta_+ - \theta_0)^2 + \frac{1}{2}(\theta_- + \theta_0 - 2\pi)^2 + (\beta - \beta_0)^2 + (\phi - \pi)^2$$

Non-dimensional approximation of the Energy behavior

Image 8: **Jesse L. Siverberg - "Using origami design principles to fold reprogrammable mechanical metamaterials"**

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Energy on a Miura-Ori origami

Equations

$l = fold\ lenght$
$k_0 = spring\ constant$
$n = number\ of\ creases$
$C = number\ of\ columns$

$$\frac{U}{k_0} = \frac{l}{2}\left((\theta_+ - \theta_0)^2 + (\theta_- + \theta_0 - 2\pi)^2 + 2(\beta - \beta_0)^2\right)$$

- l can be varied experimentally
- k_0 is constant for all experiments, same 80 $\frac{g}{cm^2}$ uncut sheef ot paper
- Variation in $(l * angle)$ implies angular changes
- Different energies → different heights!

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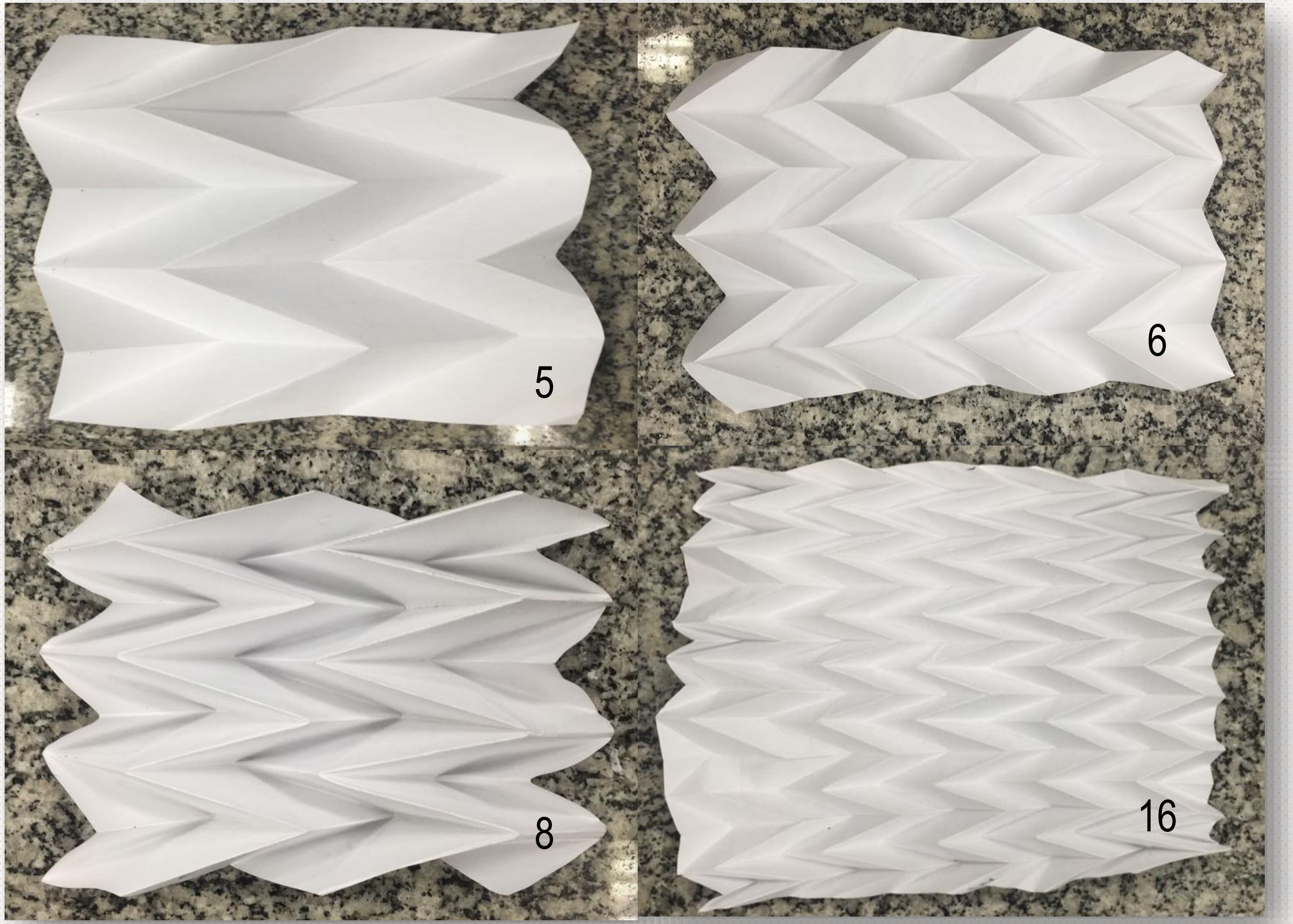
❑ Experimental considerations

- Miura-Ori with 4 different number of folds
  - 5,6, 8 ,16 folds



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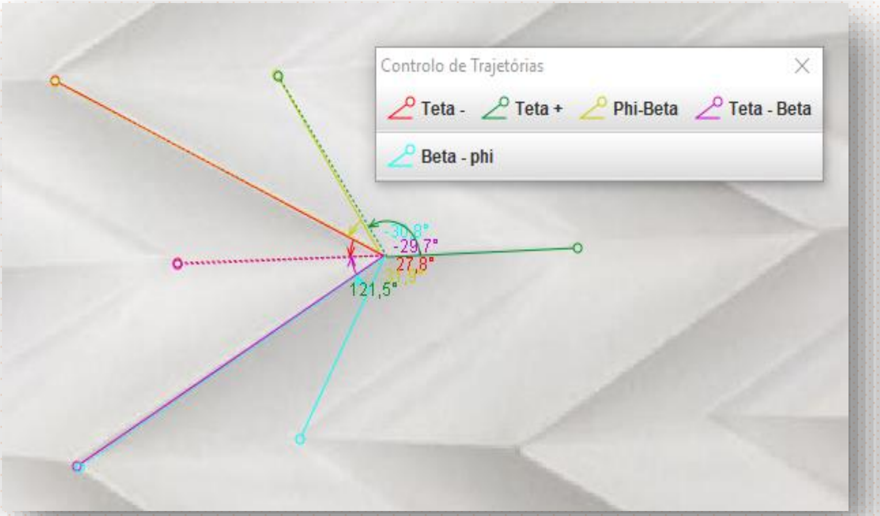
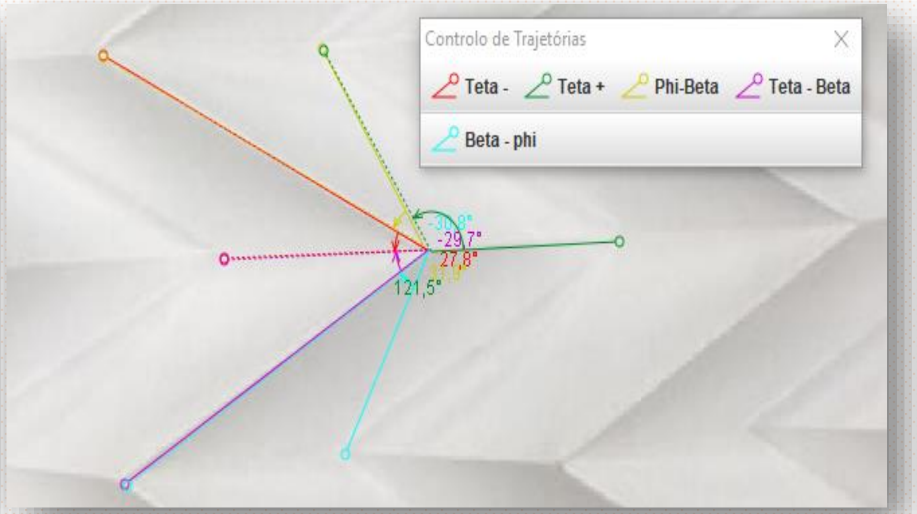
❑ Angle measurements $(\theta_0, \phi, \beta_0, \theta_+, \theta_-)$

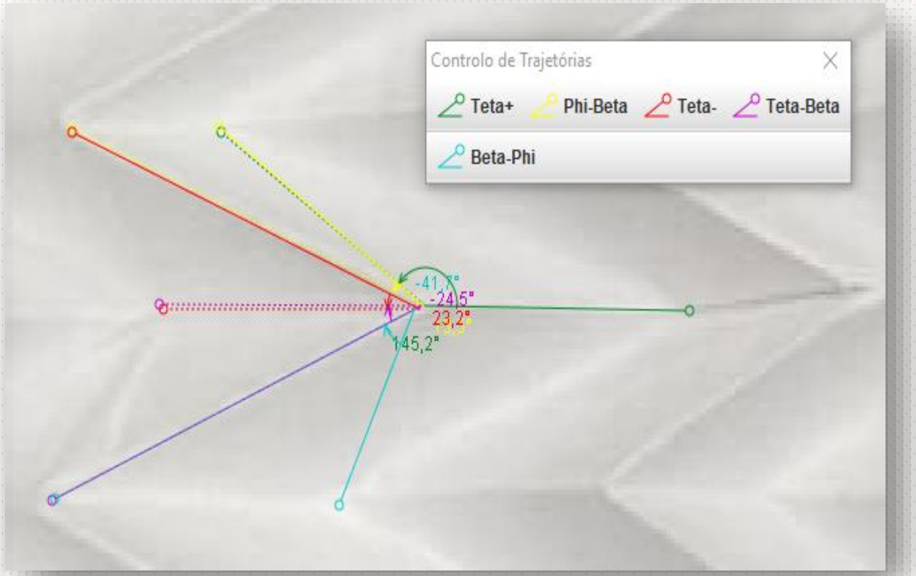


5 folds



6 folds

7 folds



16 folds

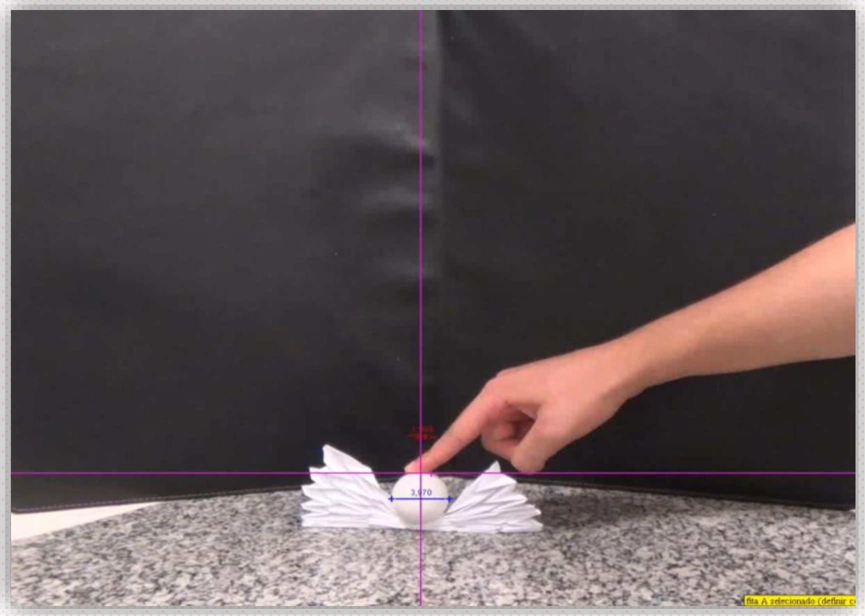
Experimental considerations

- Energy conversion

$$U_i = U_f$$

$$\begin{cases} \dfrac{U_i}{k_0} = l\left[\dfrac{1}{2}(\theta_+ - \theta_0)^2 + \dfrac{1}{2}(\theta_- + \theta_0 - 2\pi)^2 + (\beta - \beta_0)^2 + (\phi - \pi)^2\right] \\ U_f = mgh \end{cases}$$

Theoretically, we expect a linear behavior of $\frac{U_i}{k_0}$ in function of U_f!



❑ Proof of angular importance on the problem

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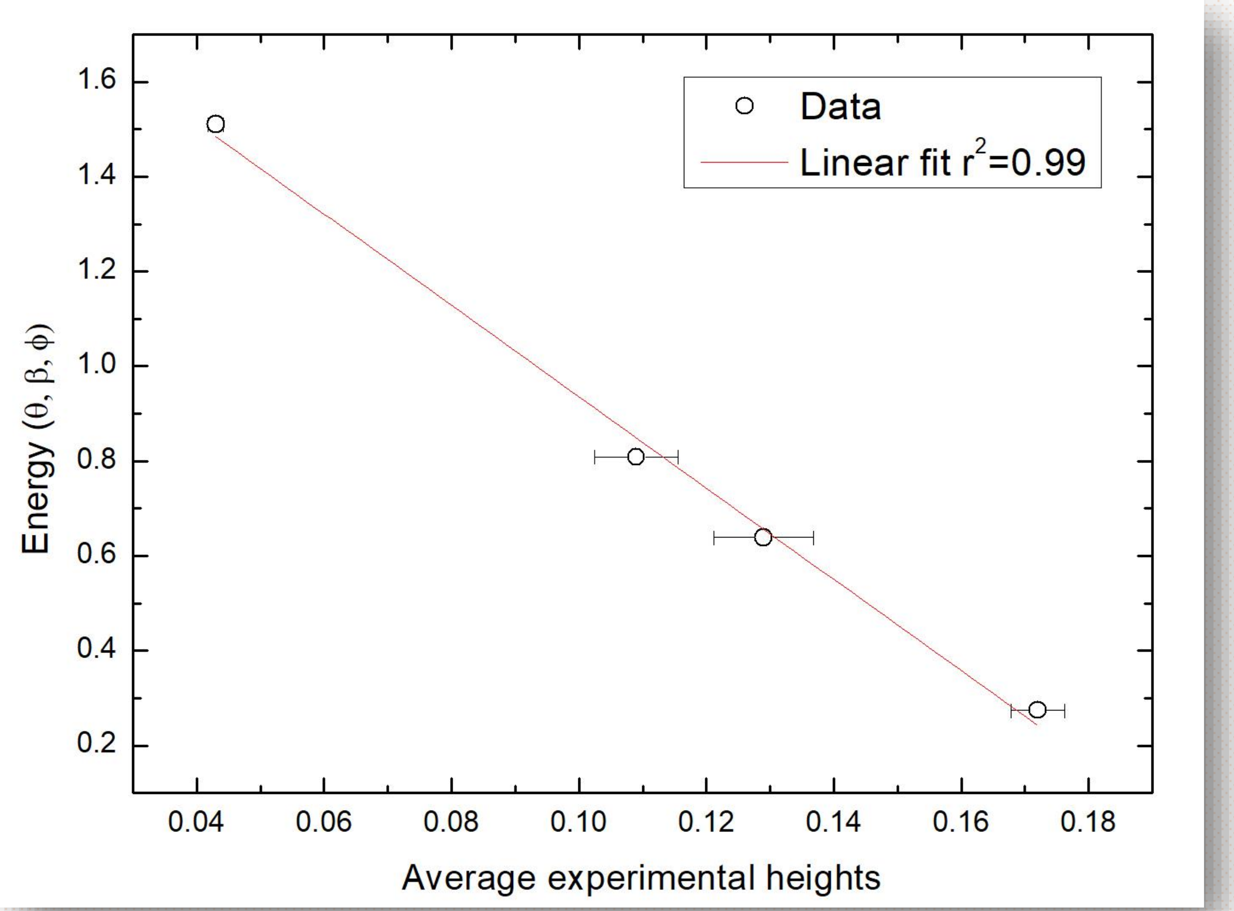
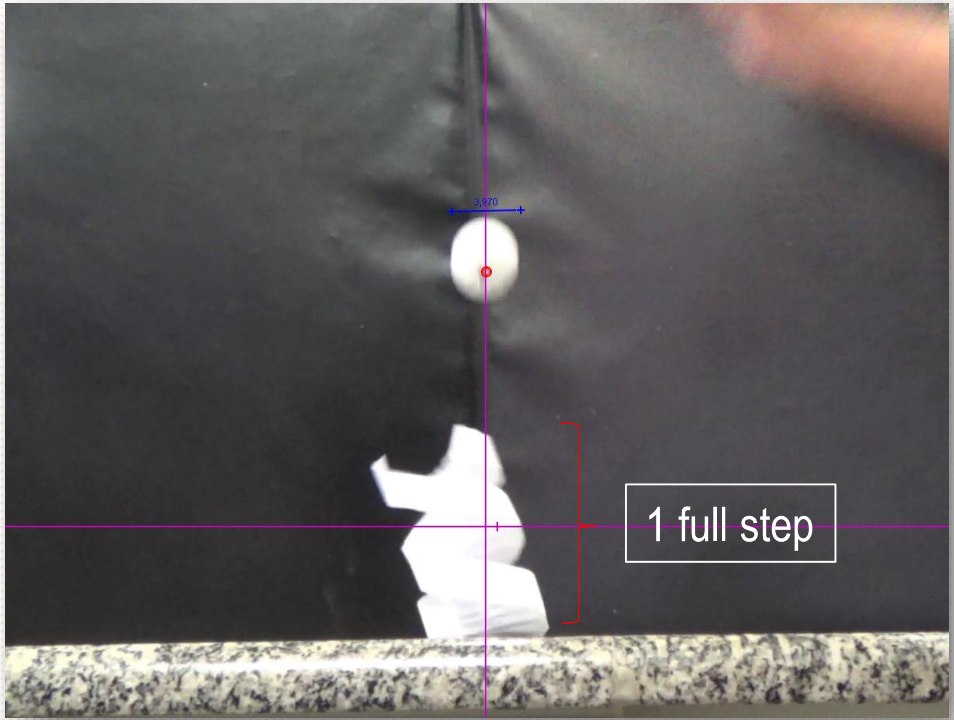


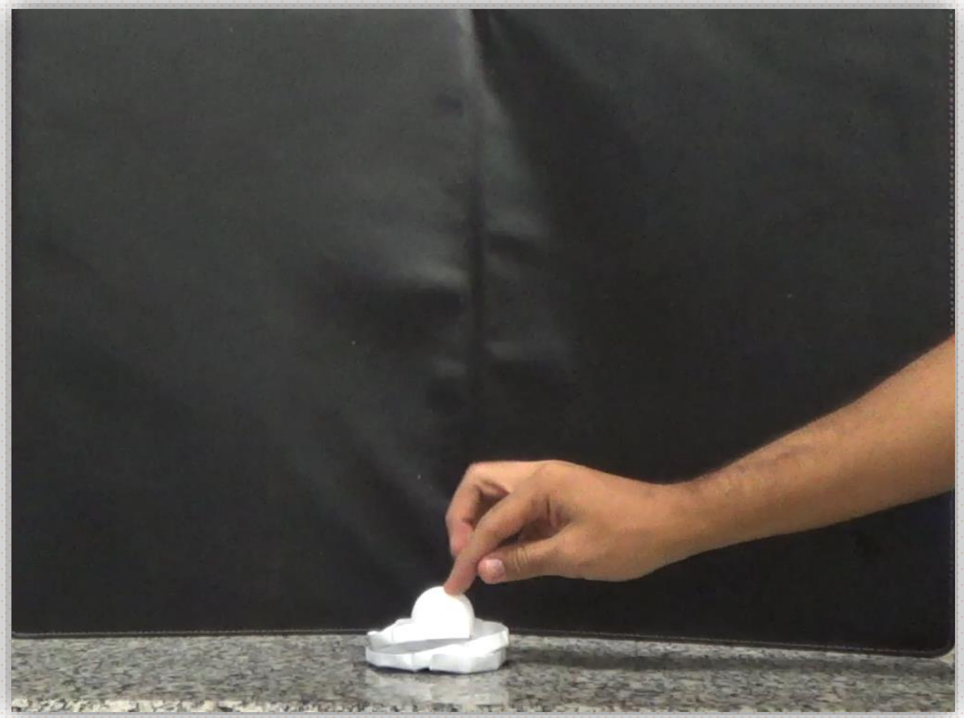
- Linear behavior is comproved for these four origamis!

$$\alpha \cong (9.6 \pm 0.4)\left[\frac{a.u.}{A_h}\right]$$

❑ Helicoidal model

○ Another way to build an origami pattern!





Measurement of a full step in centimeters

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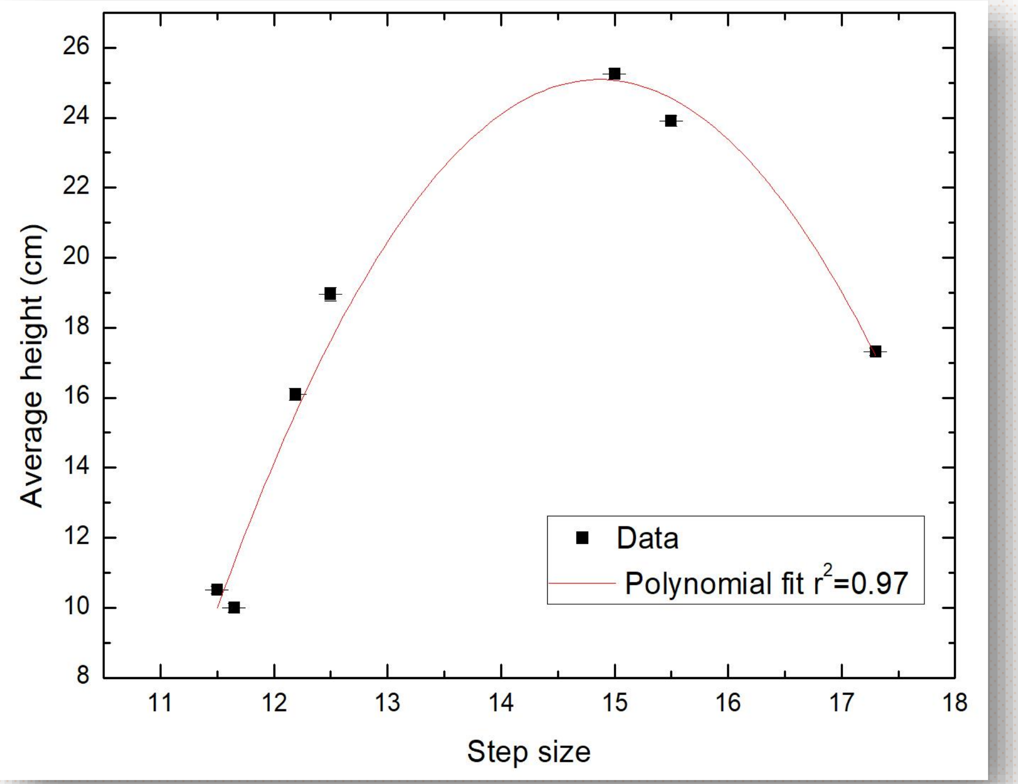
❑ Helicoidal model

- Plotting results for the helicoidal model



- Quadratic fit!
- Explanation: a direct conversion of energy from the elastic one stored in the origami (completely) into the height of the ball!

$$y = y_0 + B_1 x + B_2 x^2$$

$$\begin{cases} B_1 = (39.63446 \pm 0.465) \\ B_2 = (-1.3313 \pm 0.01) \end{cases}$$

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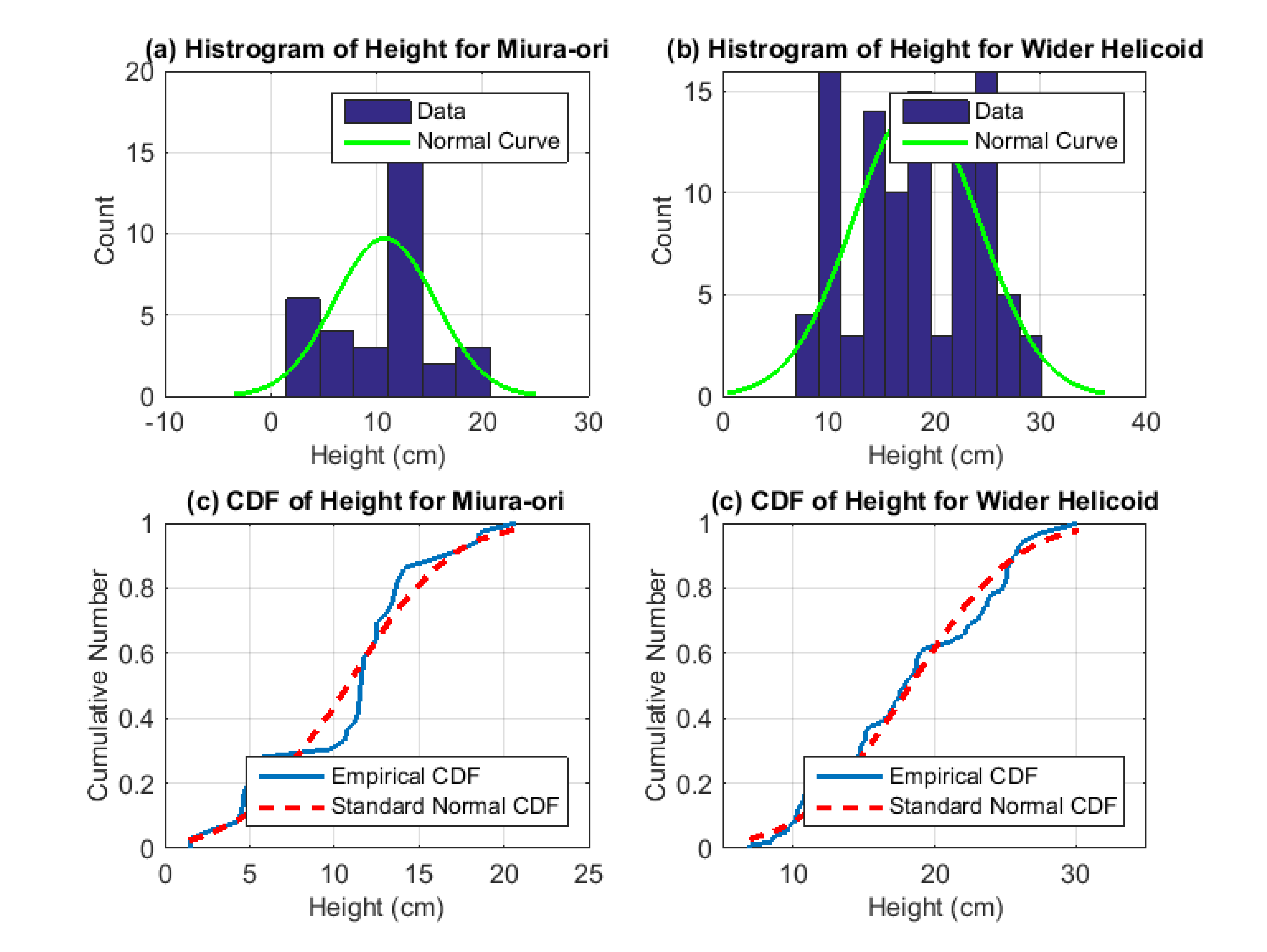
❑ Distribution for both experimental models



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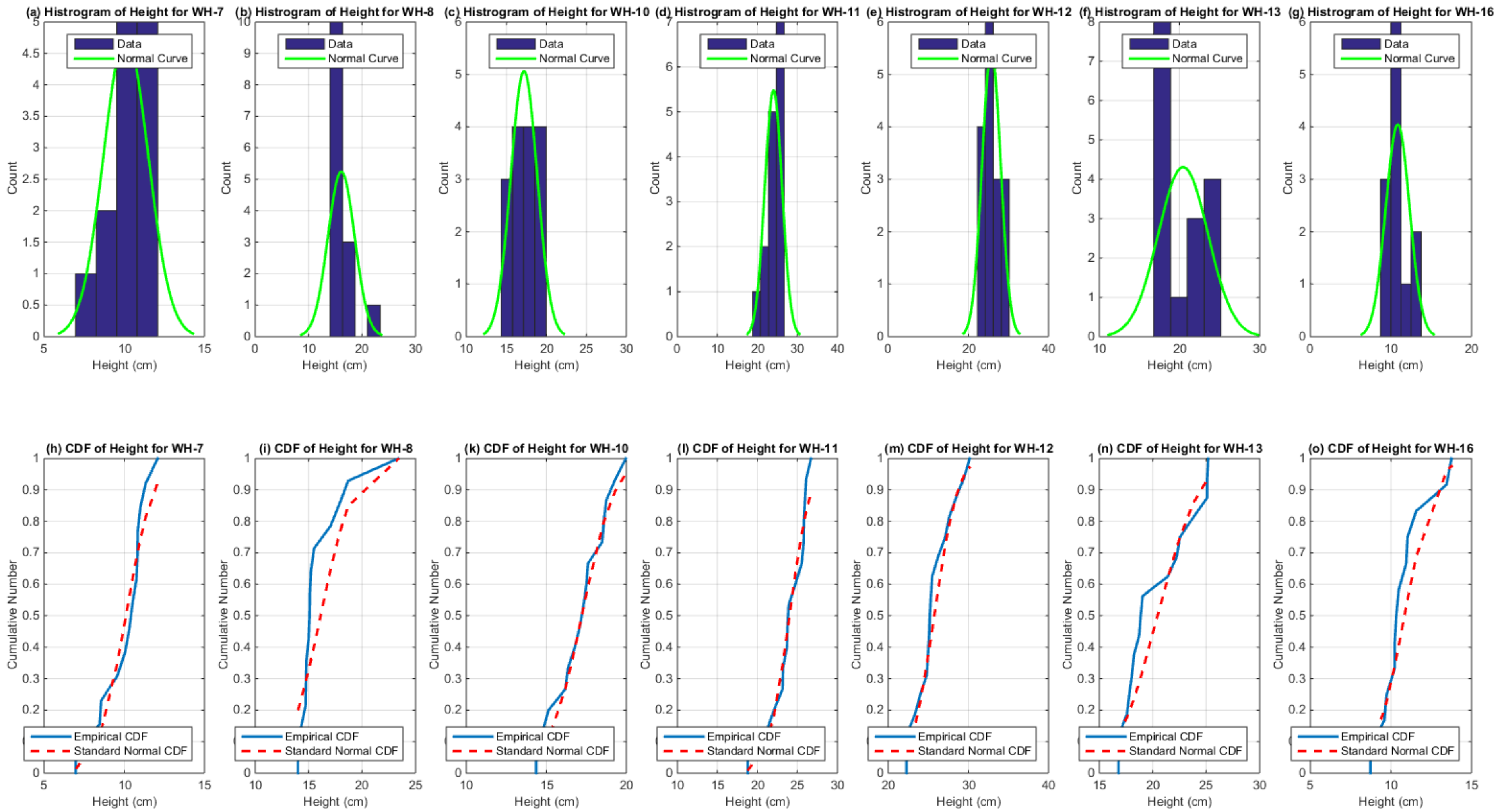
All experimental results



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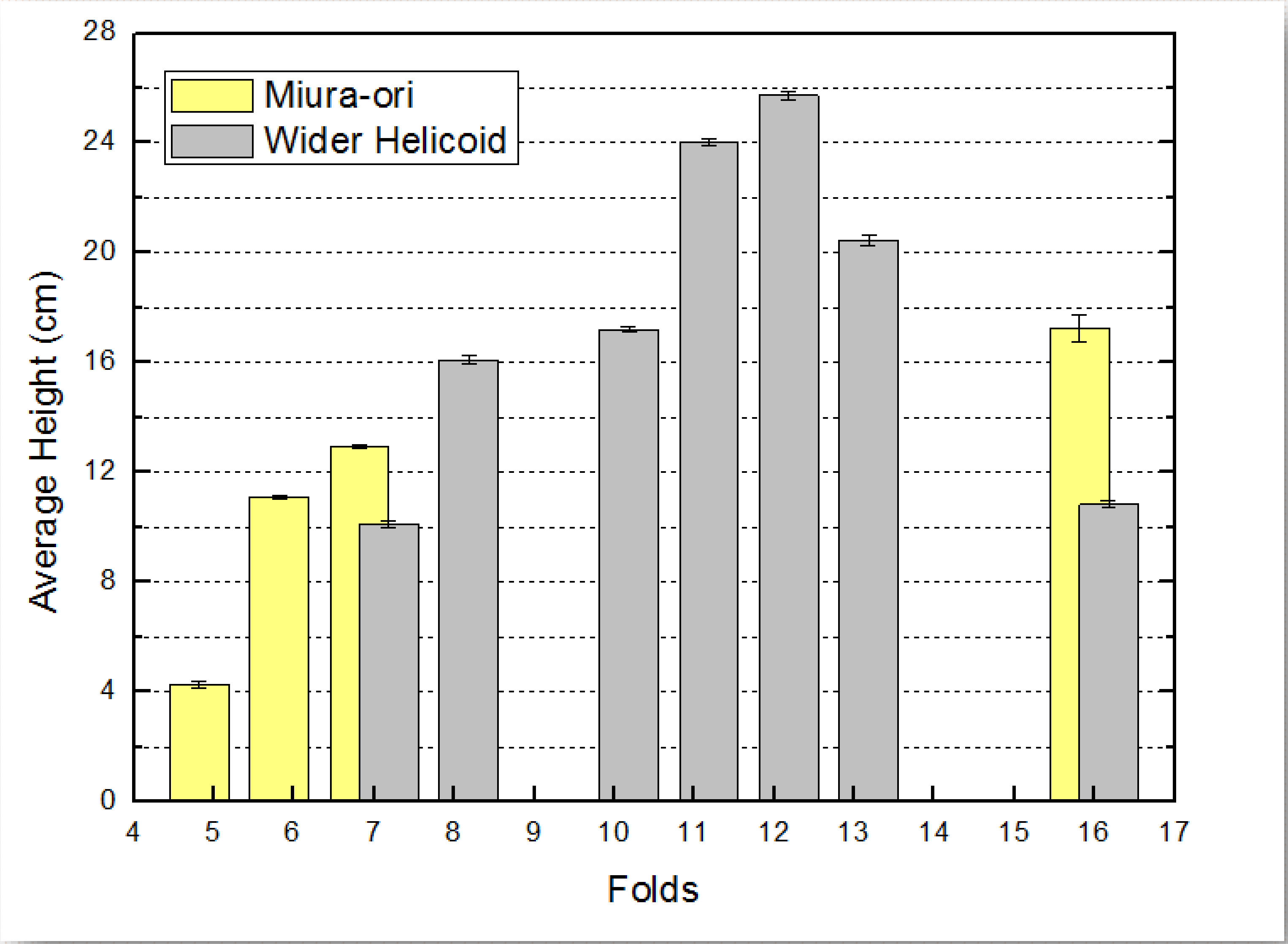
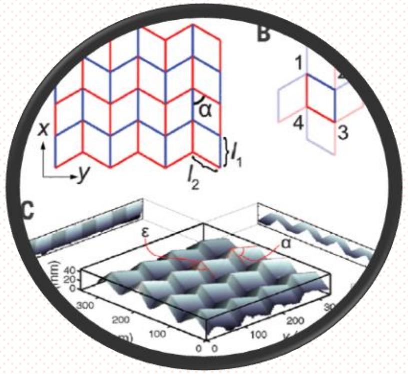
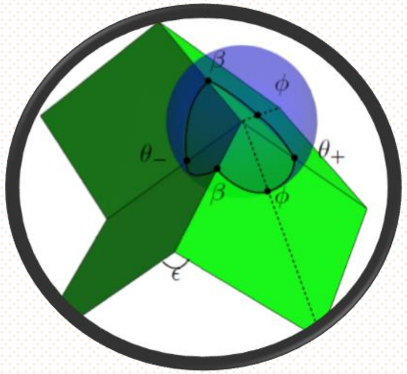
❑ Heights achieved with all origamis



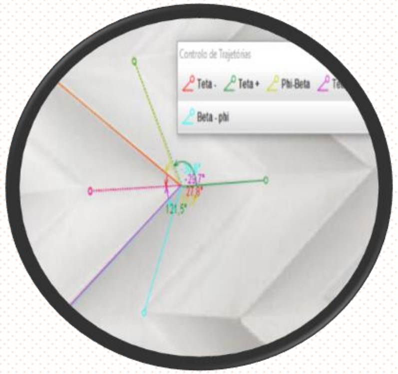
❑ Summary



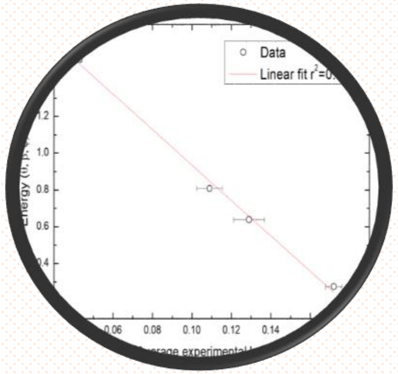
Miura-ori geometry



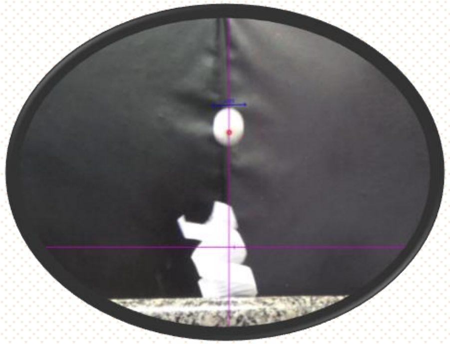
Energy



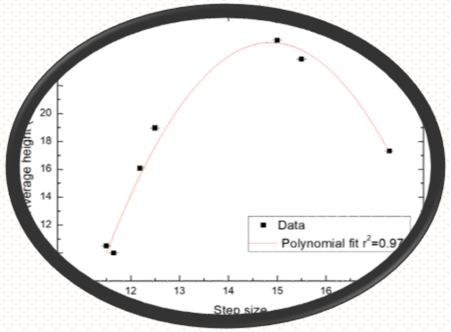
Experiments



Linear fit for results!



Helicoid model



Quadratic fit due to elastic properties

Maximized jump: helicoid model with step size of 15 cm!

$$h_A \sim (26 \pm 0.05) cm$$

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References

- [1] - Image https://www.dreamstime.com/stock-photo-wings-insect-isolated-white-background-clipping-path-image72794552
- [2] Image- https://www.asianscientist.com/2014/10/in-the-lab/making-3d-metamaterials-natural-bent/
- [3] PRL 2016, V. Brunck,***Elastic theory of origami-based metamaterials***

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❑ Distribution for all Miura-Ori results

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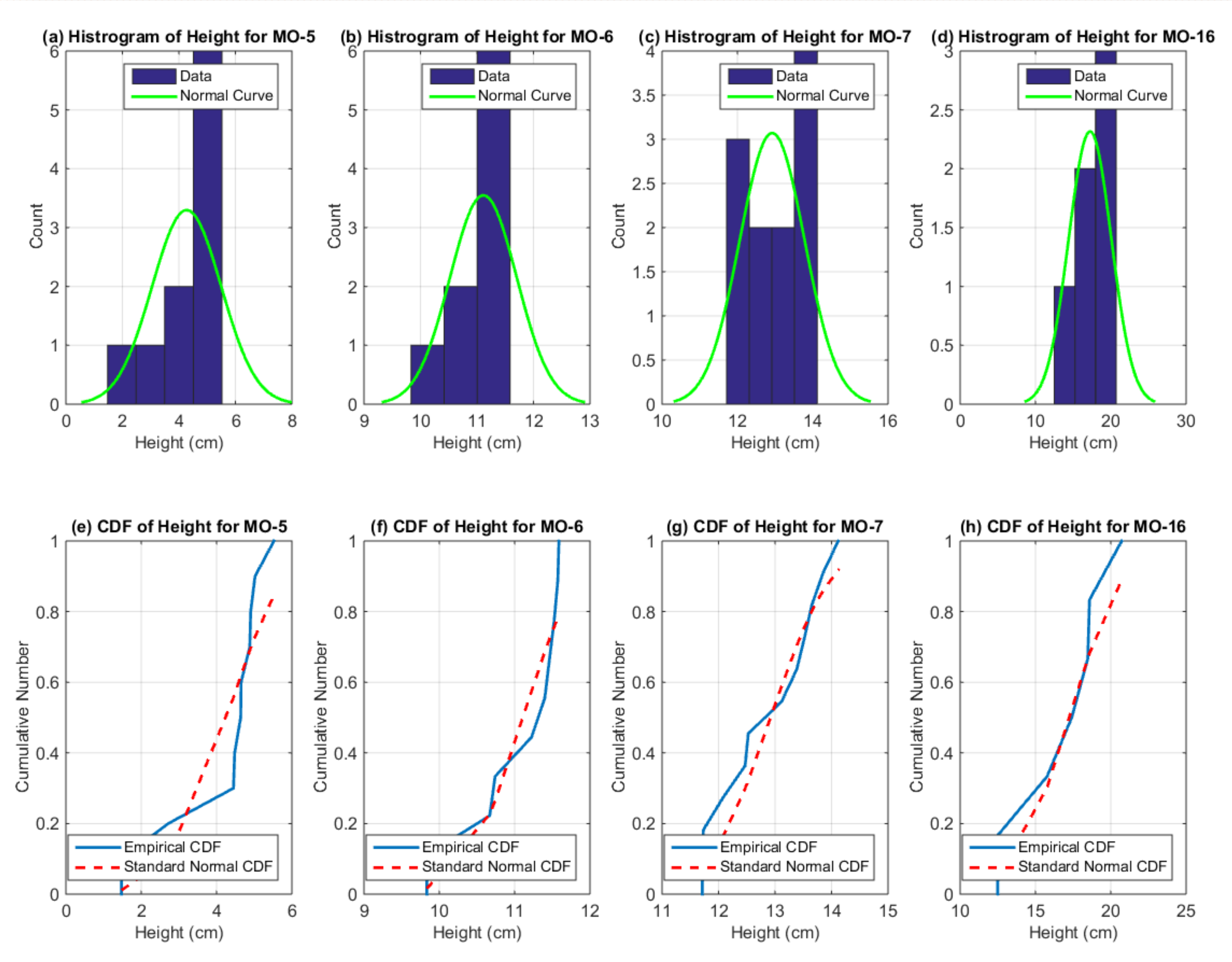

❑ Experimental results for both designs

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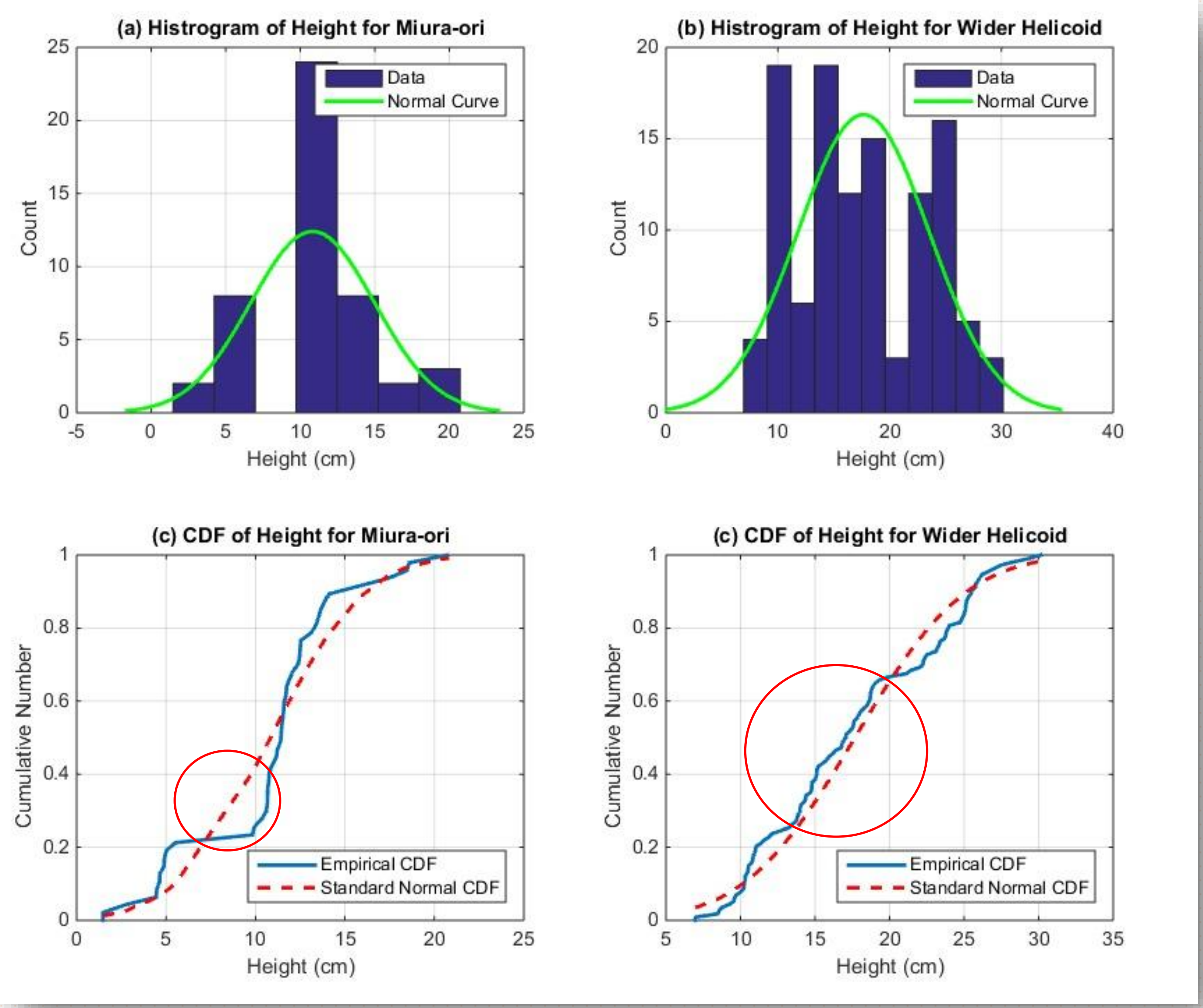

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