Ondulé | Designing and Controlling 3D Printable Springs


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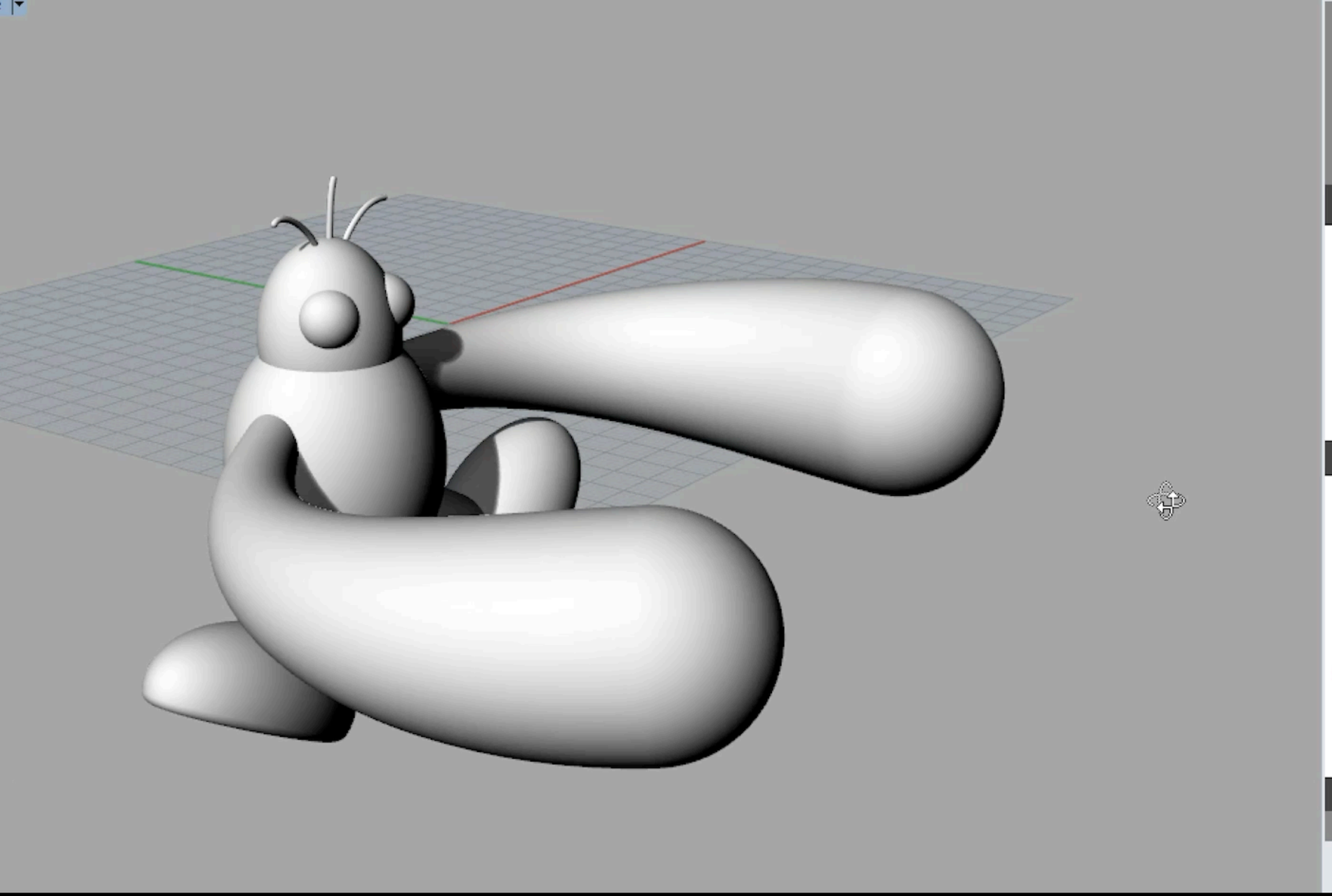
Cornell CIS
COMPUTING AND INFORMATION SCIENCE

How can we embed springs in 3D-printable objects?



Convert to spring

Change spring length

Generated Ondule Units:

Ondule Spring Customization

Basic stiffness control

Advanced spring control

Least stiff

Most stiff

Wire Thinckness 1.6mm 1.6 7.6

Turn Gap: 0.4mm 0.4 100

Ondule Joint Constraints

Individual Behavior

Linear Only

Twist Only

Bend Only

Compound Behaviors

Linear + Twist

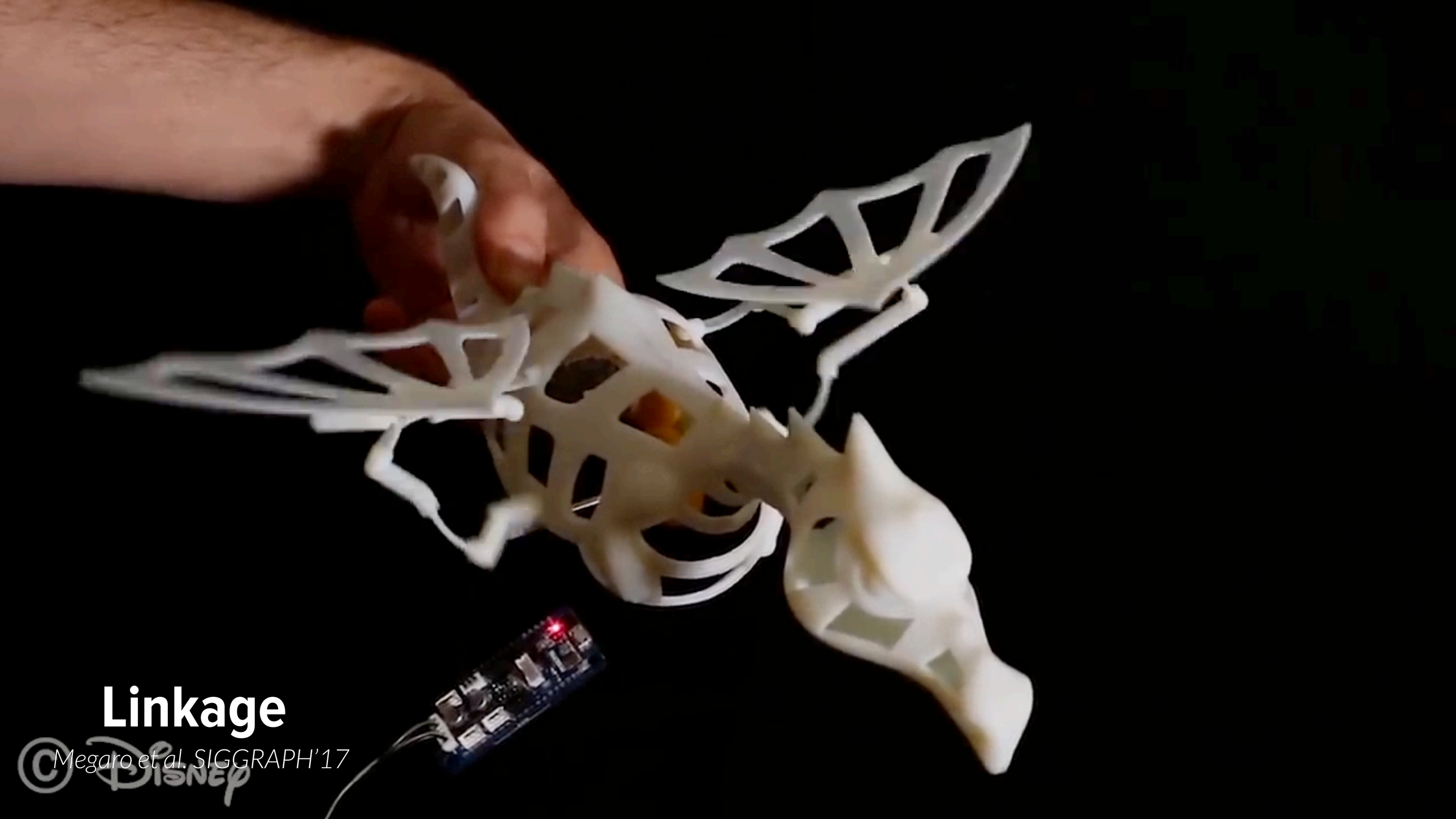
Bend + Twist

Include decorative spring layer

Making a spring man using our design tool...

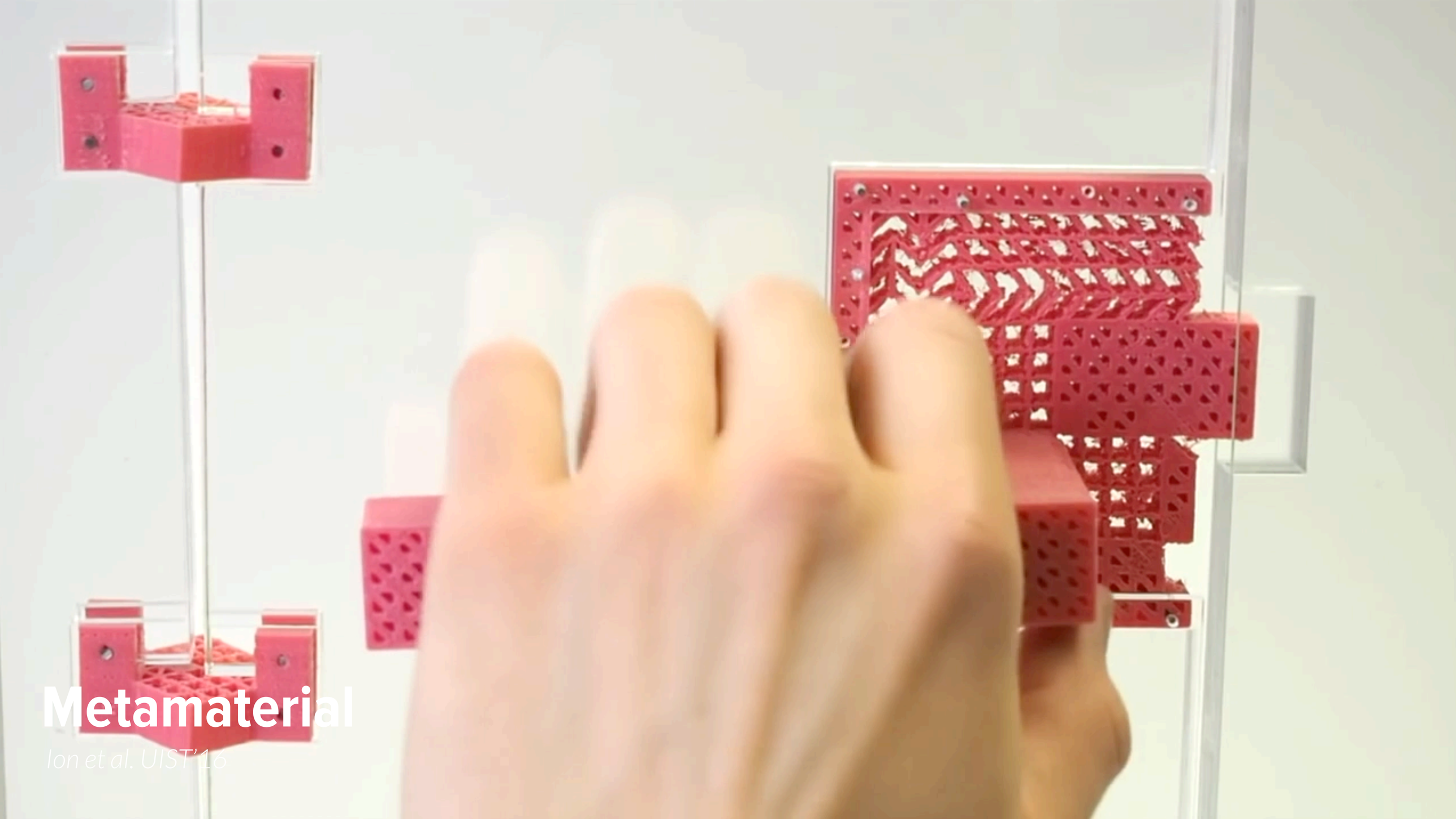
But let’s take a step back...

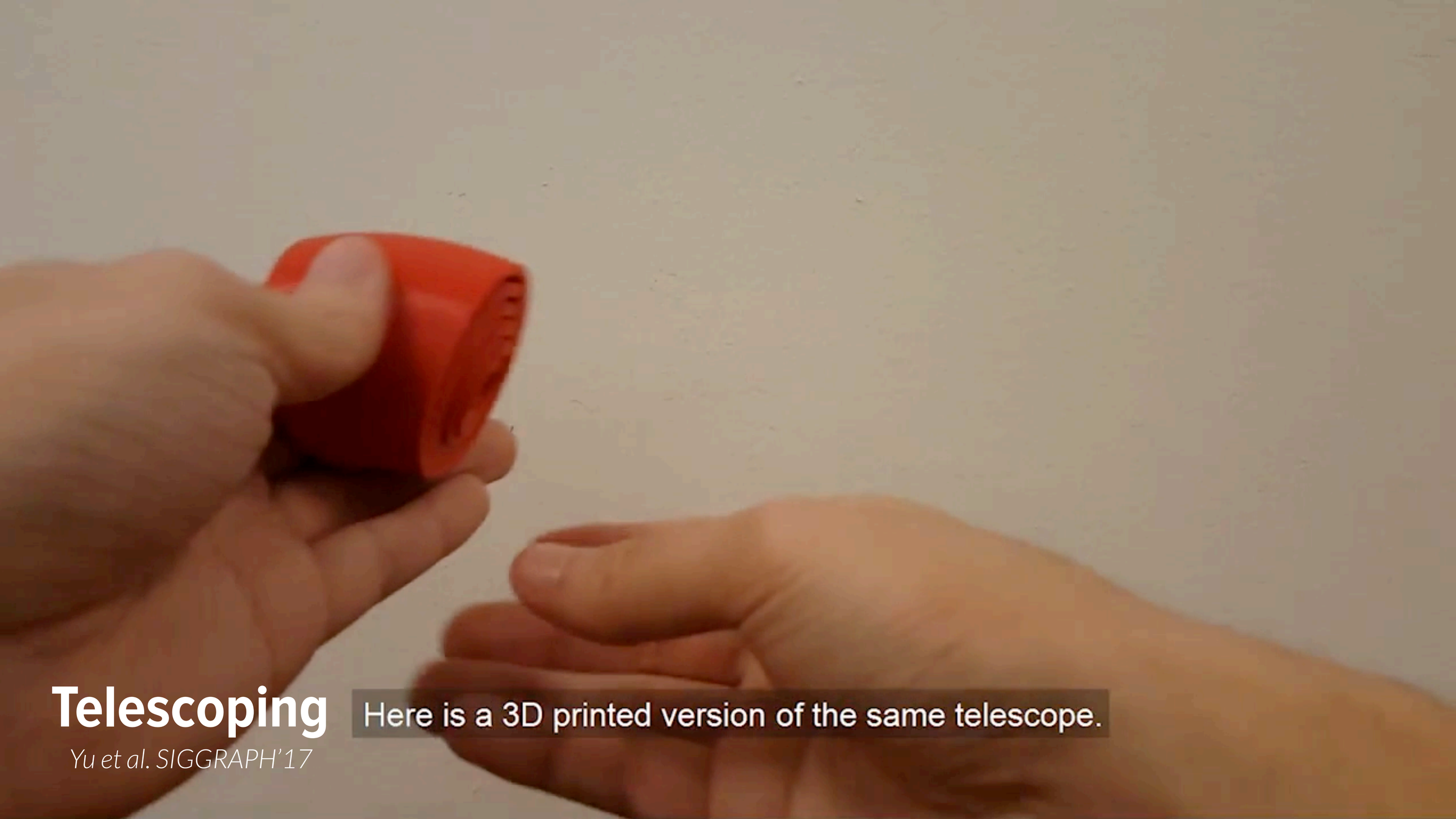
How can we add deformation to 3D printed objects?


Linkage
Megaro et al. SIGGRAPH'17
© Disney

Lattice Pattern

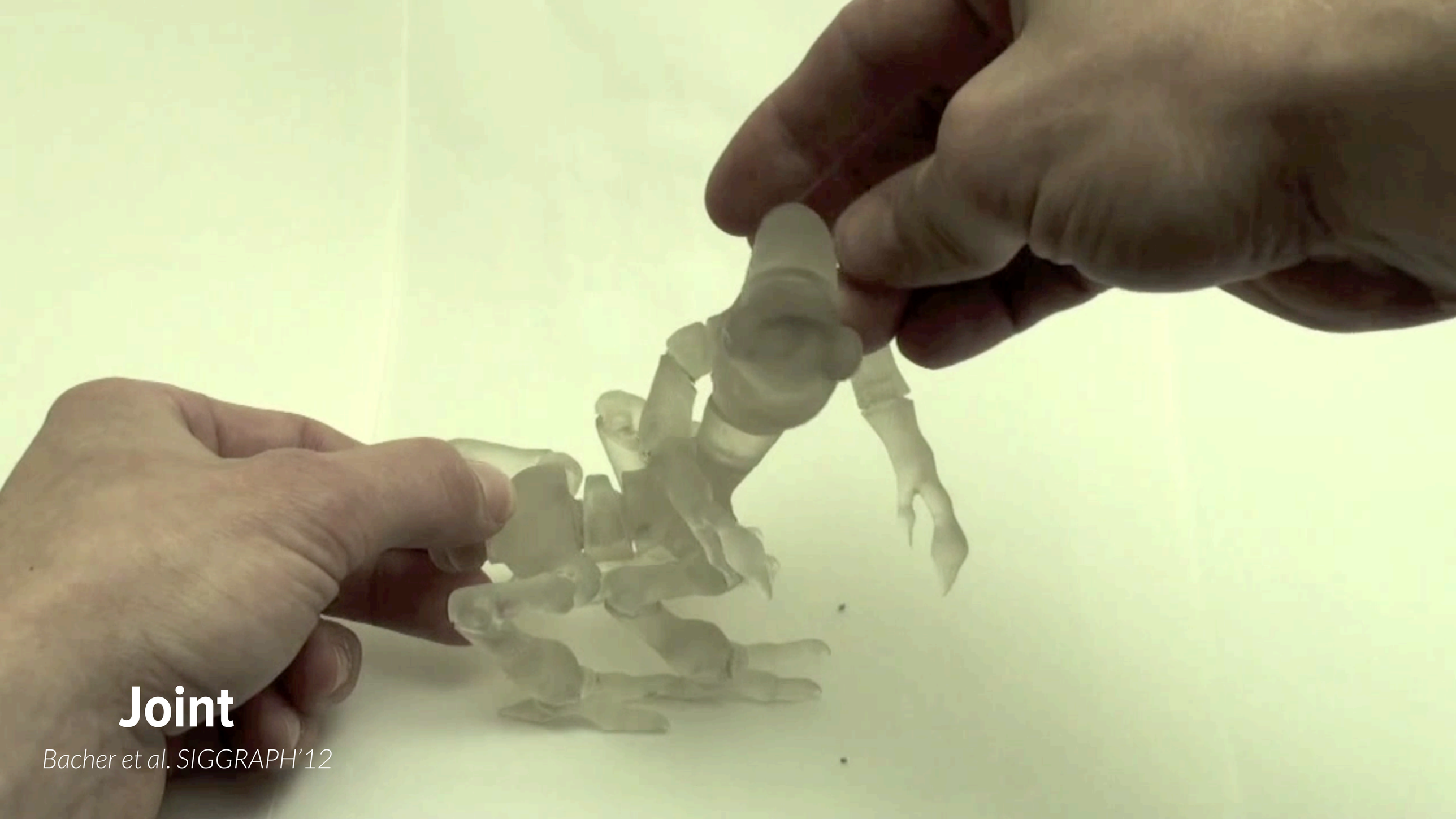
Iwafune et al. SIGGRAPH ASIA'18


Metamaterial
Ion et al. UIST'16



Telescoping

Yu et al. SIGGRAPH'17

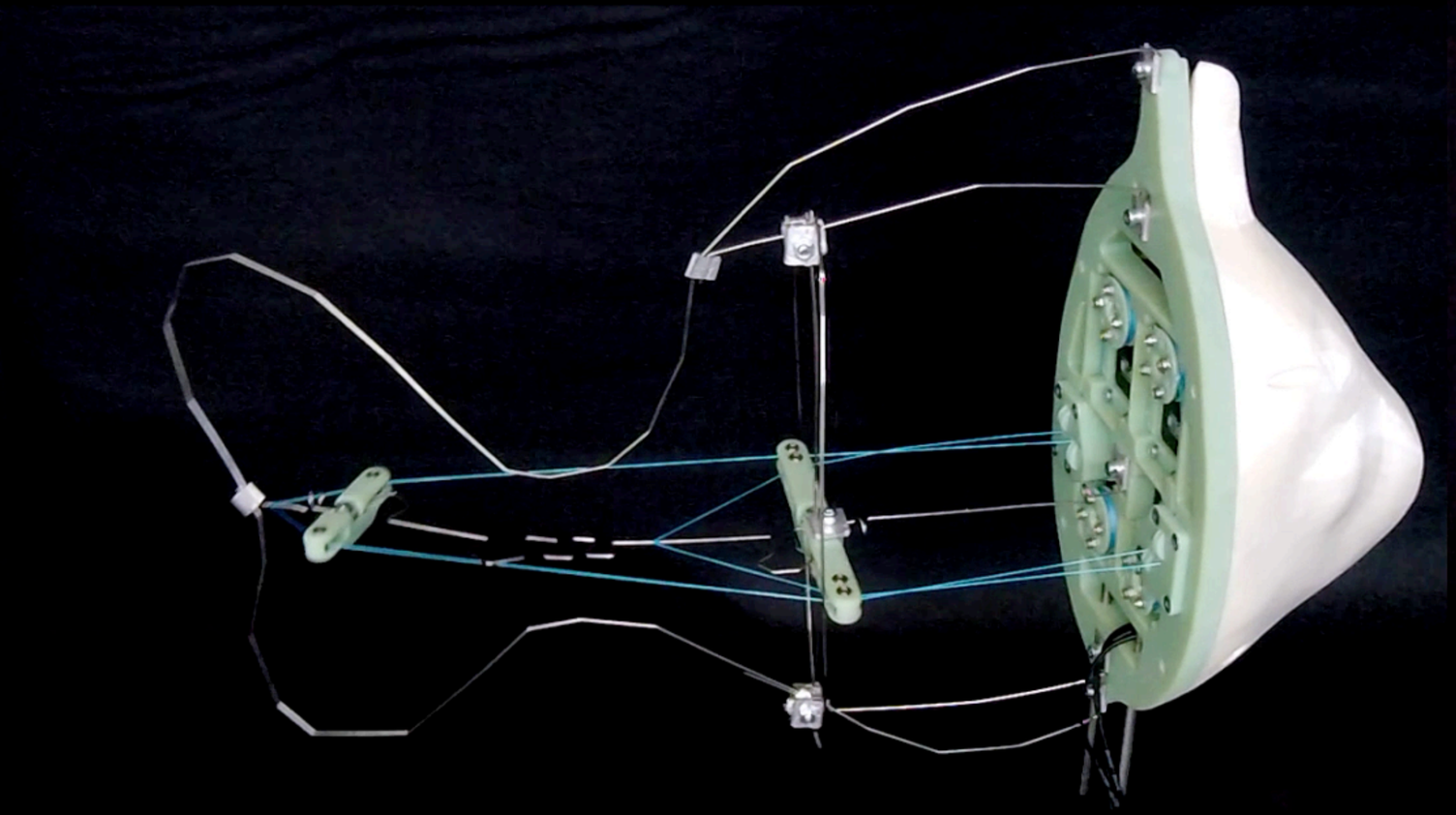


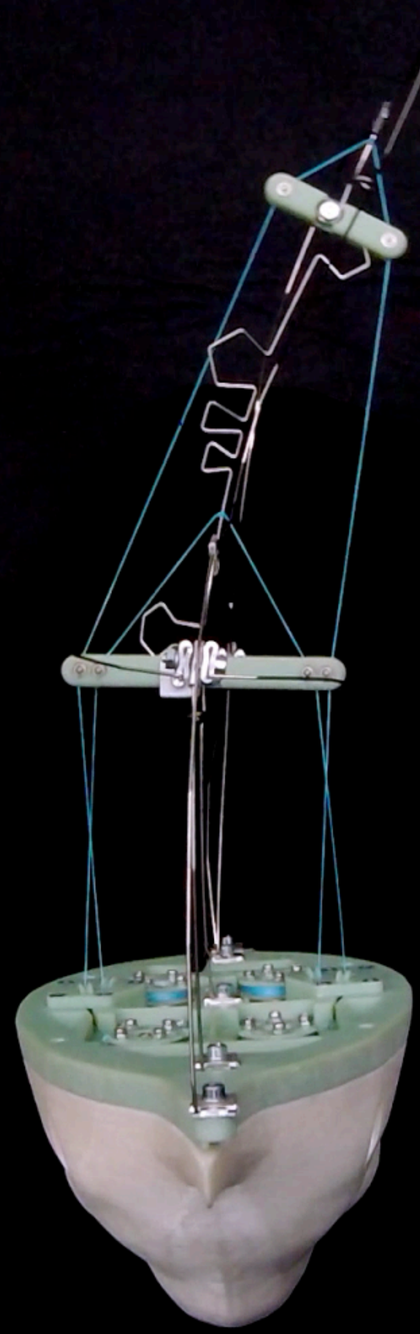
Joint

Bacher et al. SIGGRAPH'12

Side View

Top View

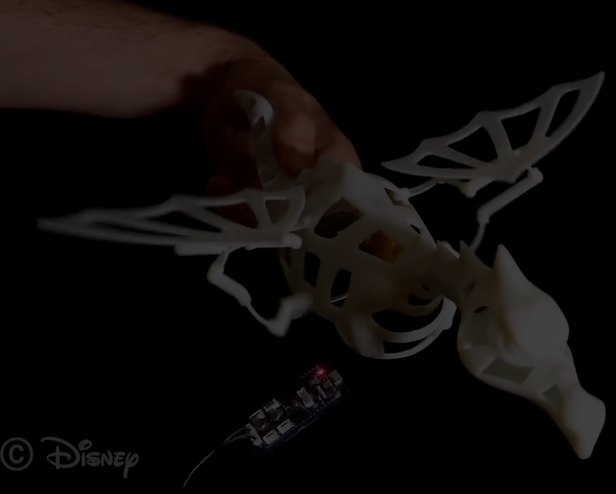




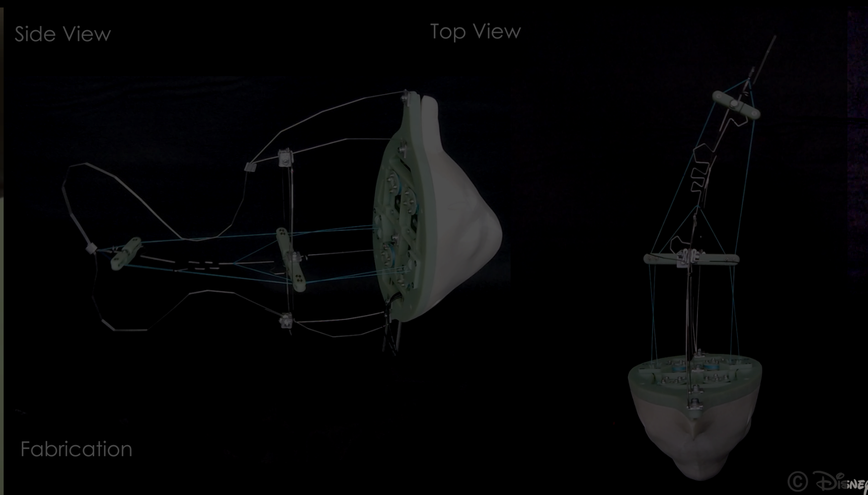
Bend-it

Fabrication

Xu et al. SIGGRAPH'18

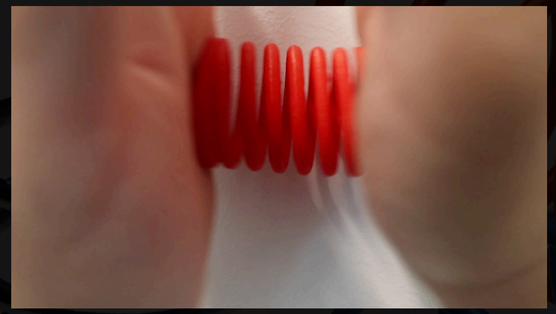


But one of the most common deformable structures in manufacturing that has not been extensively studied is

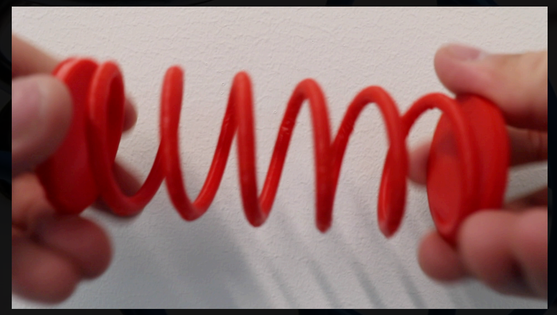


Helical Spring

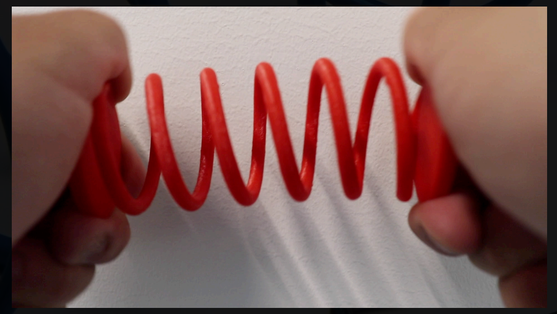
Benefits of Helical Spring



compress
extend



twist



bend

energy

YouTube Source: https://www.youtube.com/watch?v=hMAgMDgi7xQ

shape approximation

Key Challenges

- The mechanical performance of 3D-printed helical springs are not known
- Design, customize, and control spring deformation behaviors can be difficult

Research Questions

- Do 3D printable springs follow mechanical theory?
- How can we isolate the deformation behaviors in a spring?
- How to lower the barrier to create and control springs in CAD design tools?

RQ1: Do 3D printable springs follow mechanical theory?

Mechanical Experiments

Material Properties

Young's modulus (E)

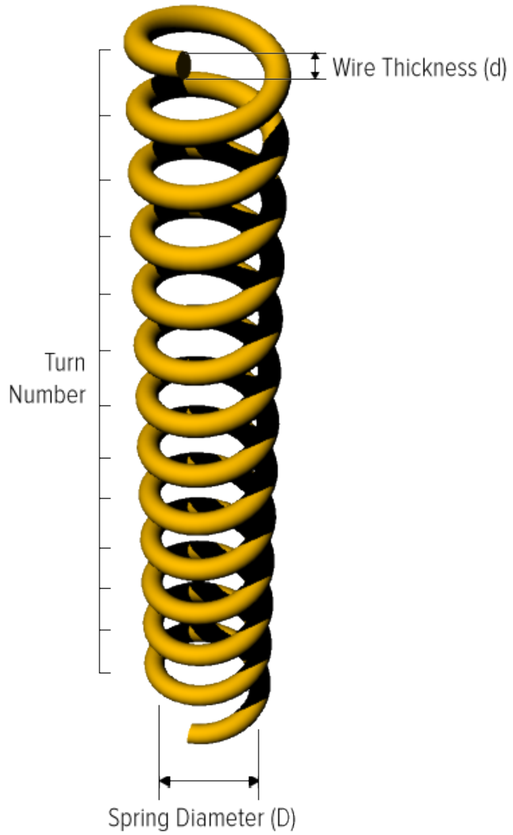
Shear modulus (G)

Spring Parameters

spring diameter (D)

wire thickness (d)

number of coil turns (N)



Experiment 1:

3D-printed rod material property tests (E & G)

Experiment 2:

3D-printed spring tensile tests

Experiment 3:

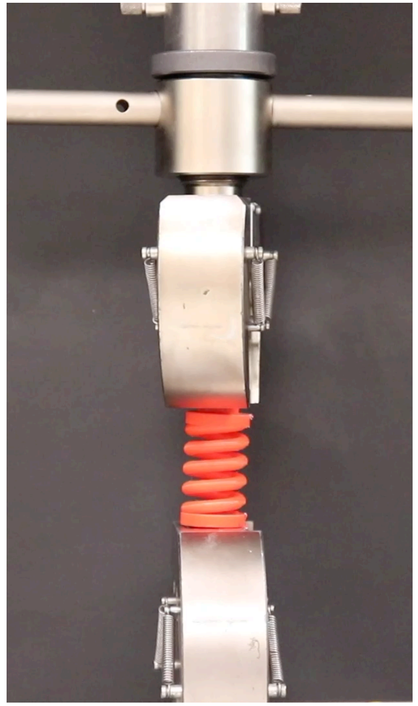
3D-printed spring torsion tests

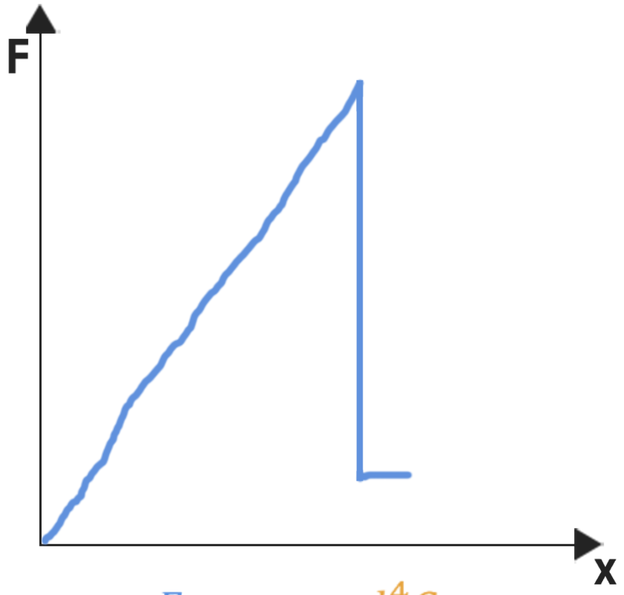
3D-Printed Spring Tensile Tests

Condition	Wire Thickness (mm)	Diameter (mm)	Length (mm)	Turn Number
Wire Thickness (*d*)	2, 3.4, 4.8, 6.2, 7.6	32	50	
Diameter (*D*)	4	25, 30, 50, 60	50	
Spring Length (*L*)	4	32	25, 45, 65, 85	
Turn Number (*N*)	4	32	50	4, 6, 8, 10

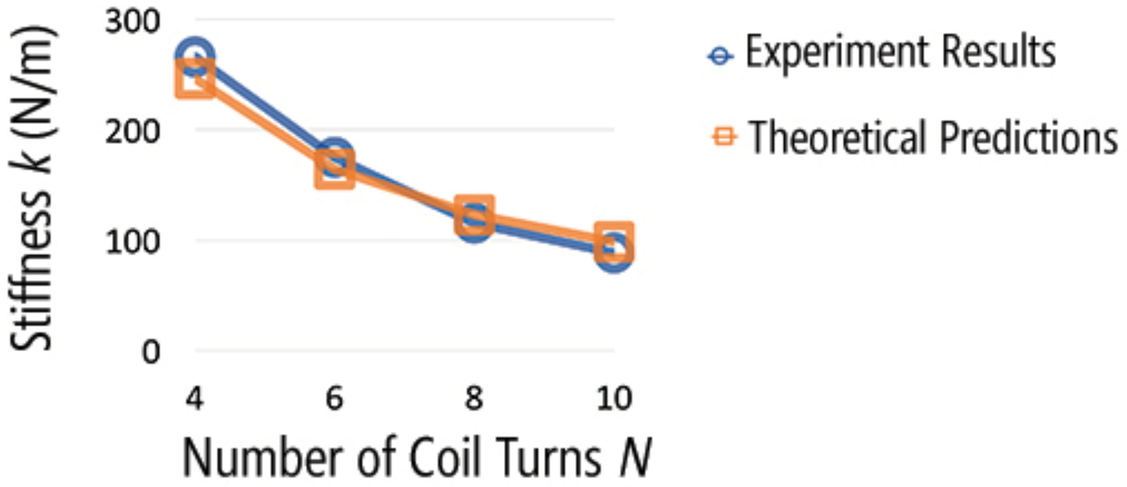
100% infill
lines infill pattern
90° printing angle

17 3D-printed springs



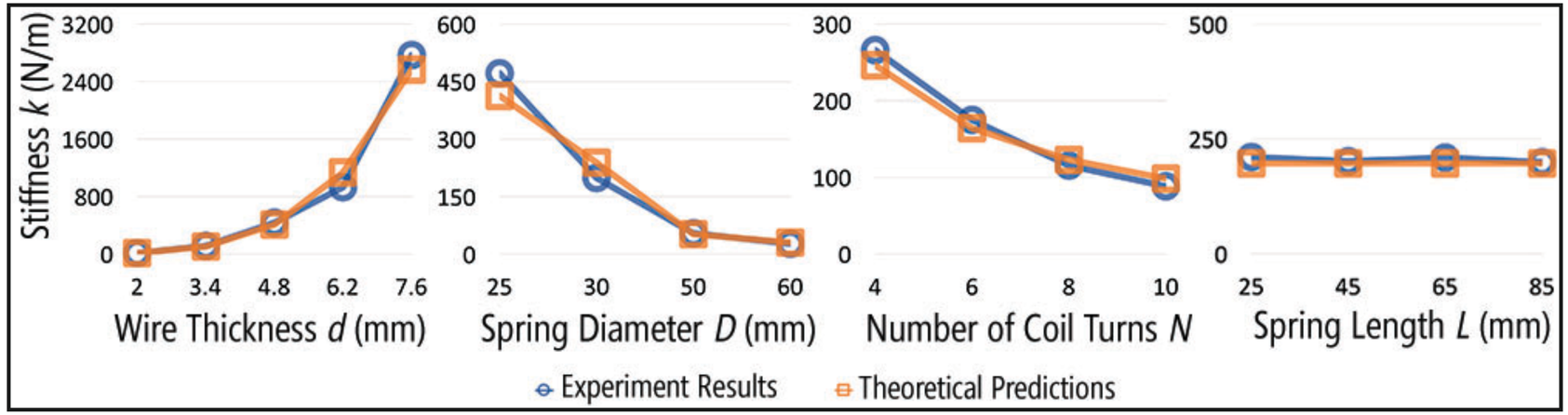


$$k = \frac{F}{x} \quad k' = \frac{d^4 G}{8D^3 N}$$

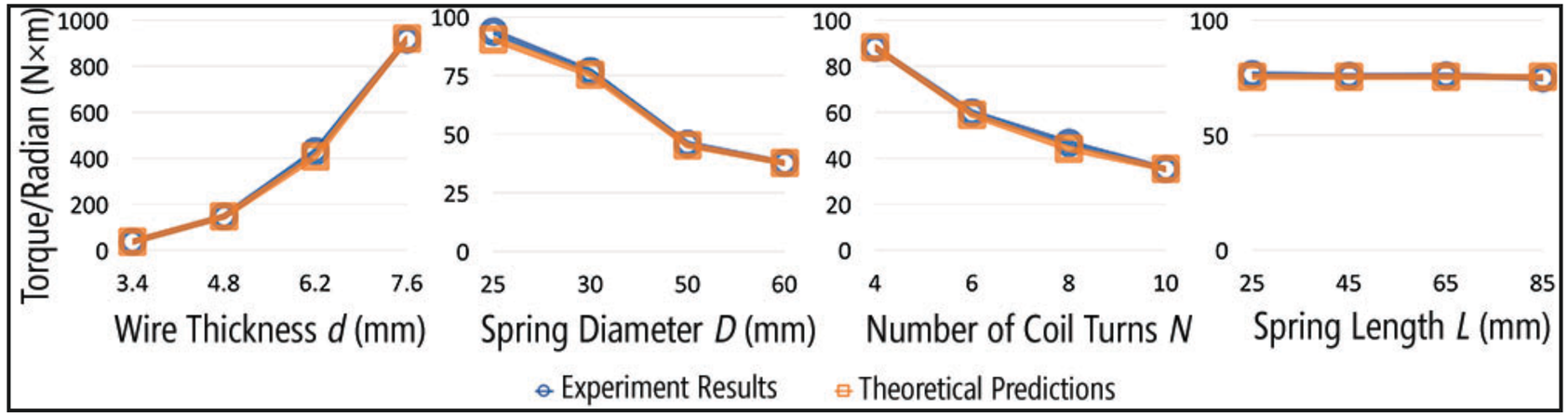


3D-Printed Spring Tensile & Torsion Test Results

Tensile Test Result



Torsion Test Result



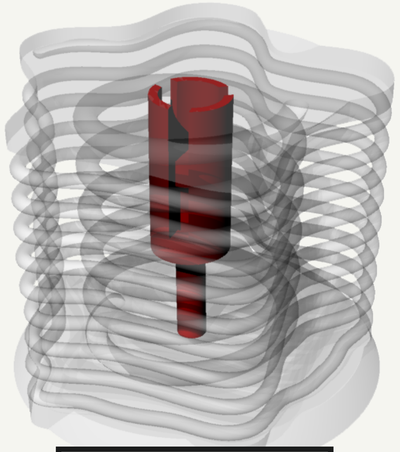
The tensile and torsion behaviors of 3D-printed helical springs closely mirror theoretical predictions

RQ2: How can we isolate the deformation behaviors?

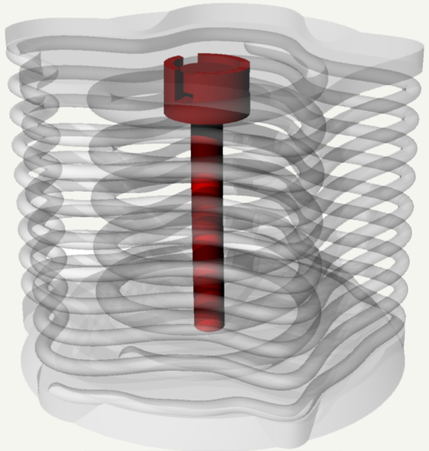
Deformation Techniques

Ondulé Deformation Techniques

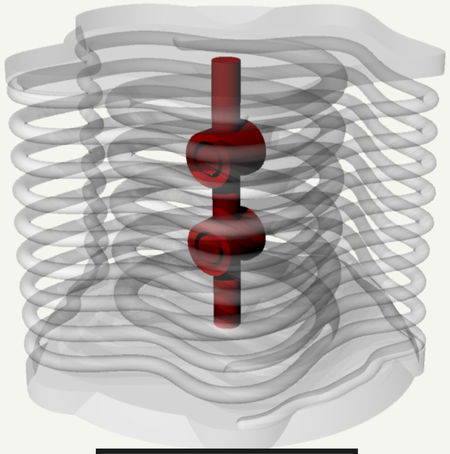
Individual Behavior



Linear Only
Prismatic Joint

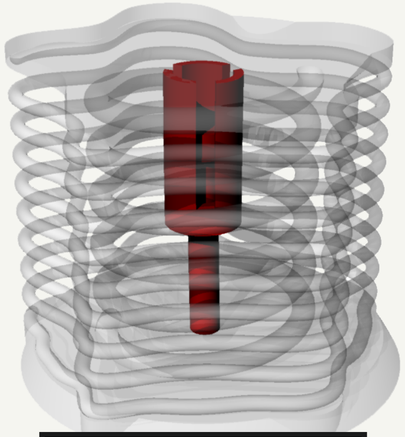


Twist Only
Revolute Joint

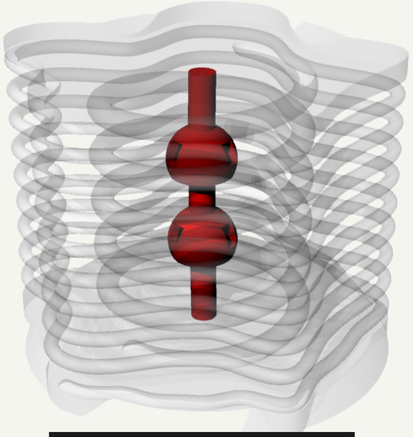


Bend Only
Chained Knuckle Joint

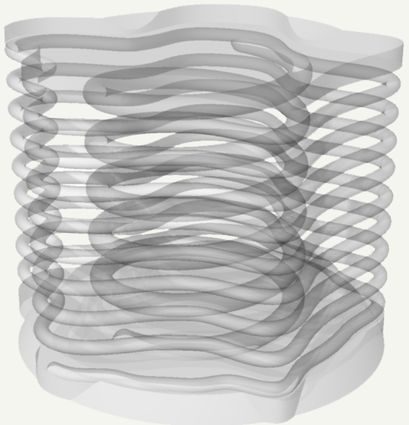
Compound Behavior



Linear + Twist
Cylindrical Joint



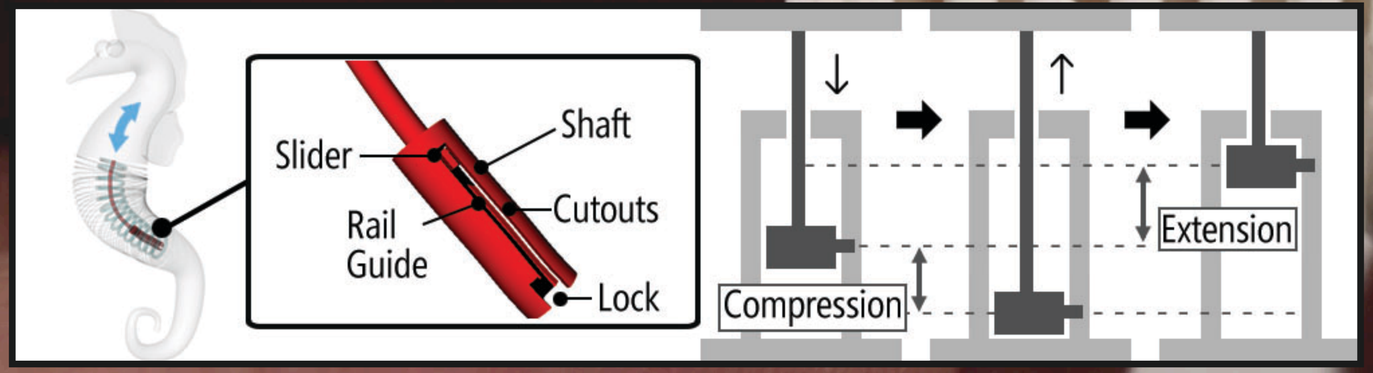
Bend + Twist
Chained Ball Joint



Freeform
(no joints)

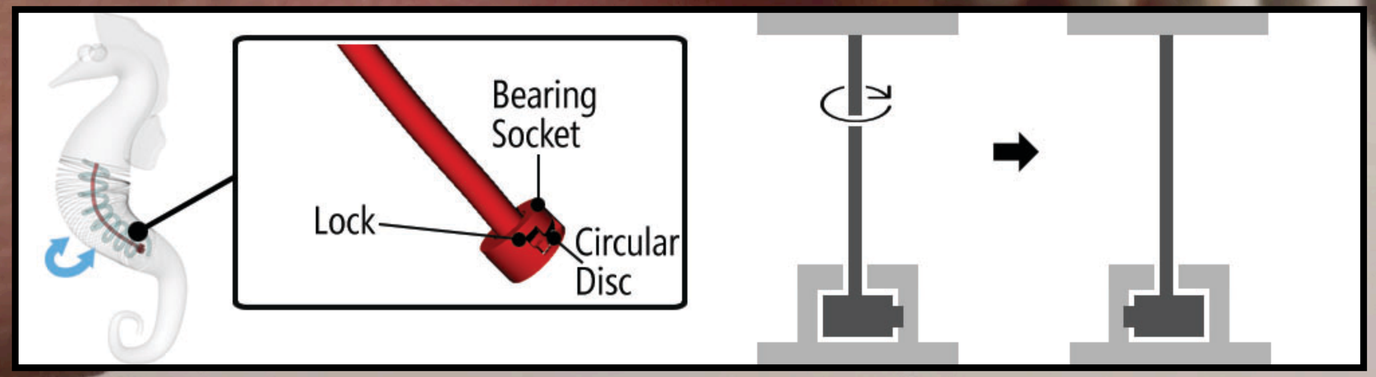
Ondulé Deformation Techniques

Compress + Extend Only: Prismatic Joint



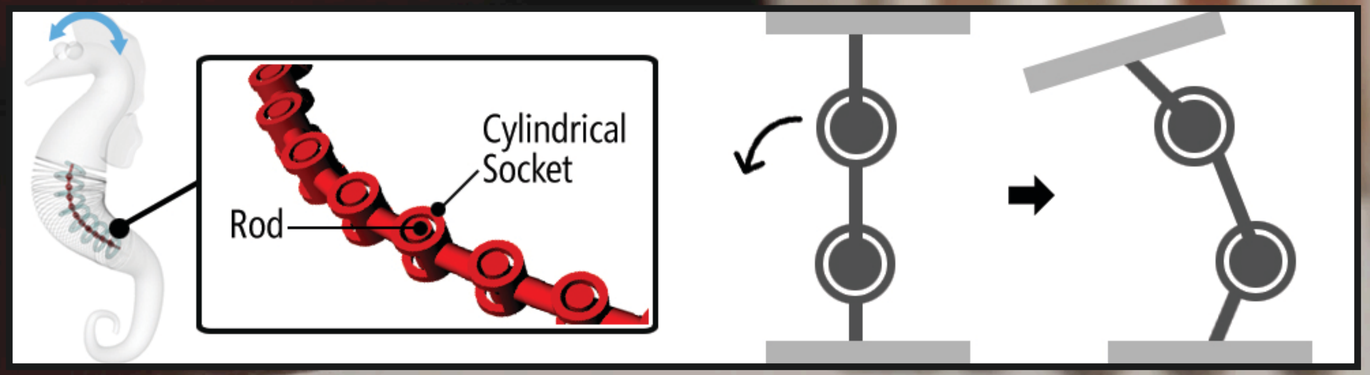
Ondulé Deformation Techniques

Twist Only: Revolute Joint



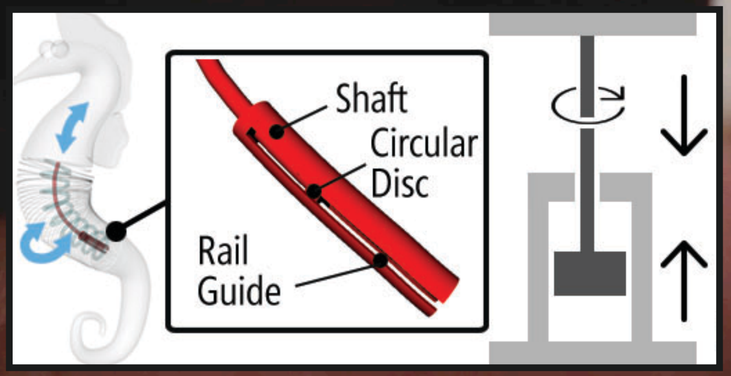
Ondulé Deformation Techniques

Bend Only: Chained Knuckle Joint



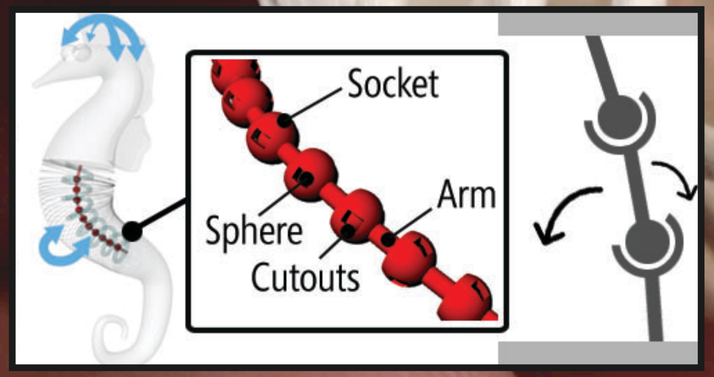
Ondulé Deformation Techniques

Linear + Twist: Cylindrical Joint

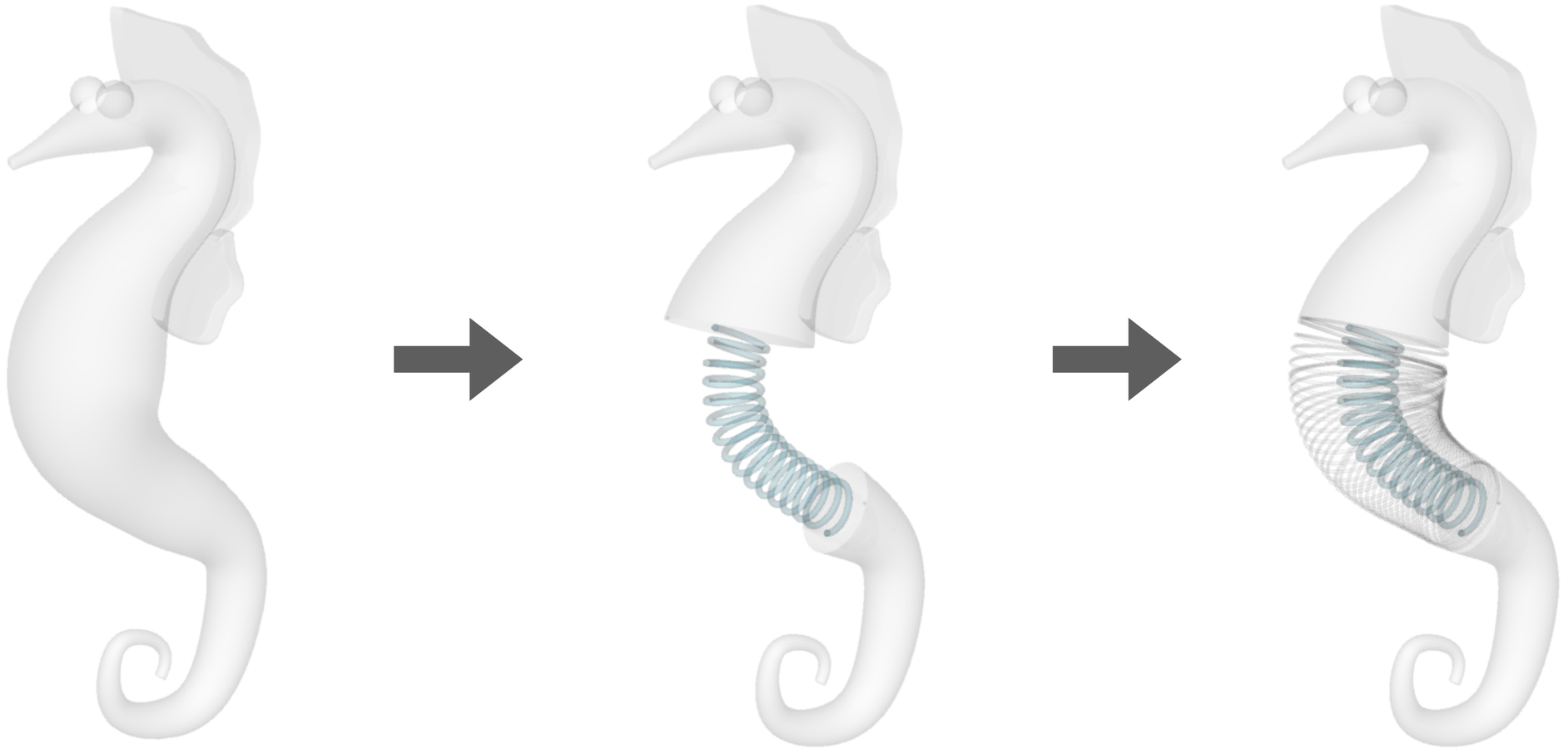


Ondulé Deformation Techniques

Bend + Twist: Chained Ball Joint



Ondulé Decorative Spring



Original Model

Deformation Spring

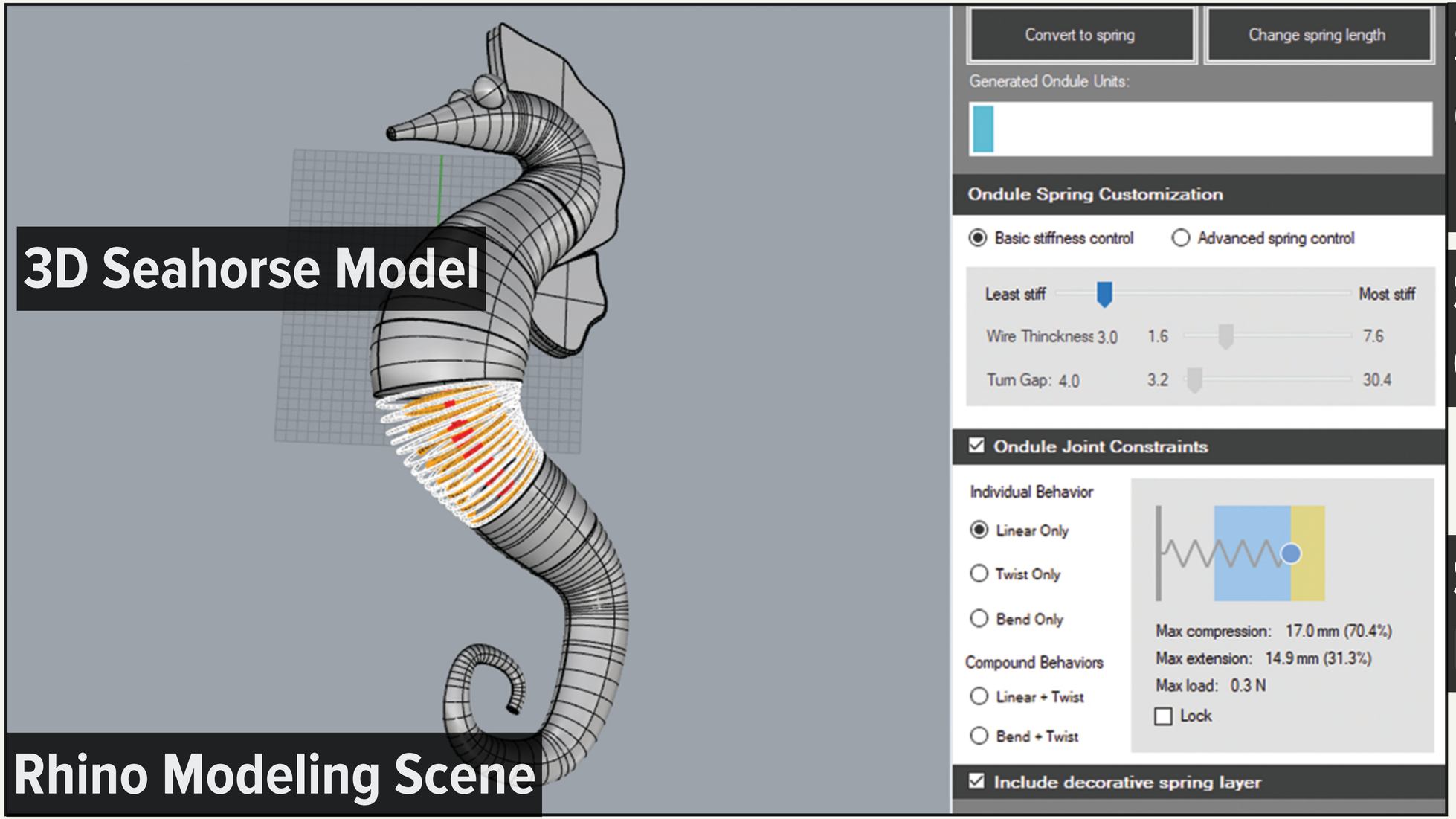
Deformation + Decorative Springs

RQ3: How to lower the barrier to create and control springs in CAD design tools?

Ondulé Design Tool

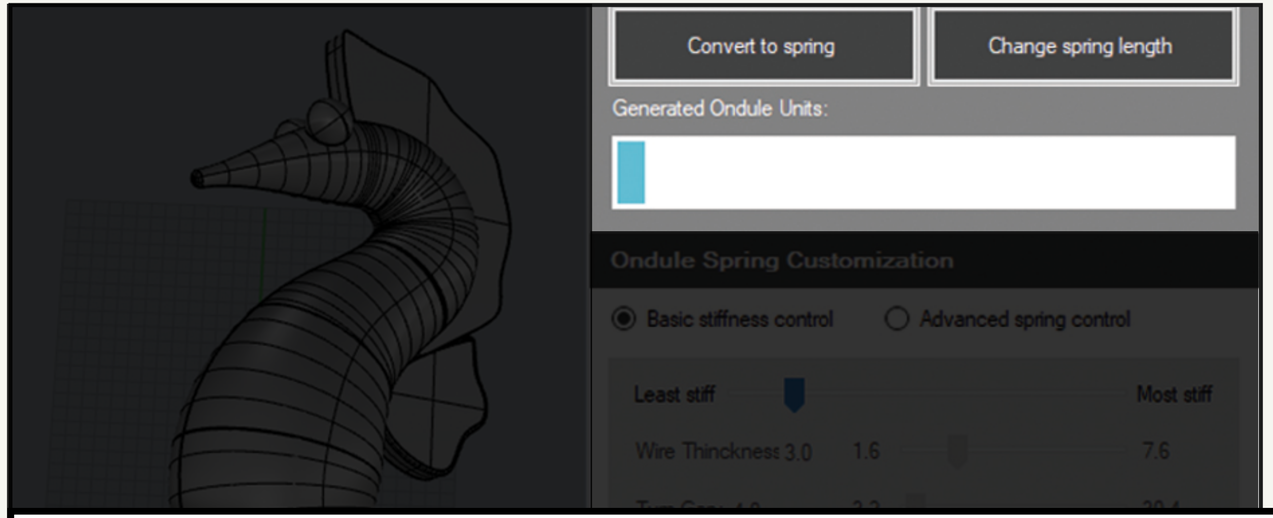
allows novice designers to add deformation behaviors to static 3D-printed objects using embedded springs and joints.

Ondulé Design Tool

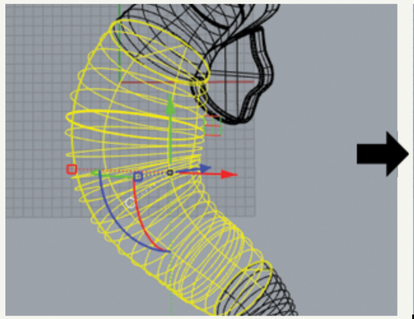


Ondulé Design Tool

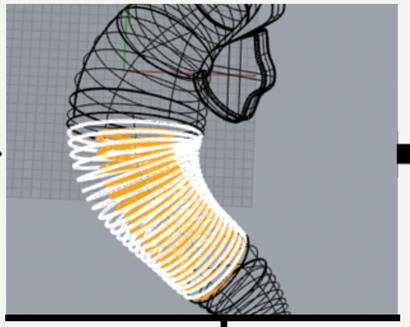
Spring Generation



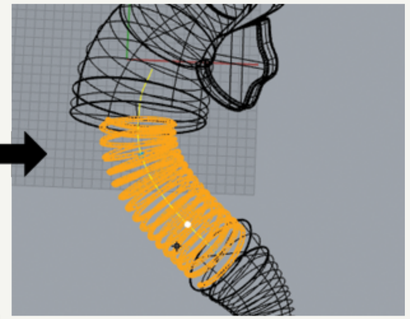
1. Body Selection

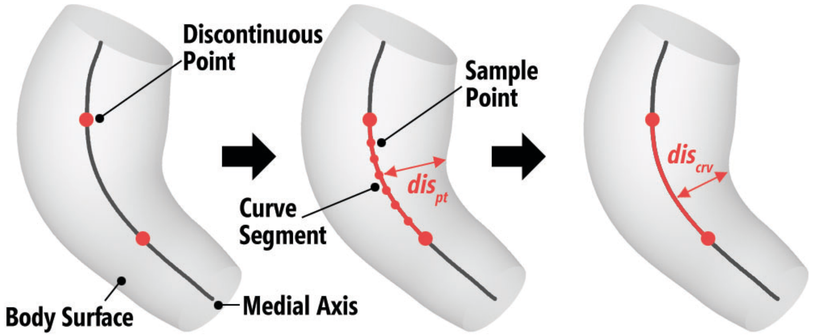


2. Spring Generation



3. Spring Length Change



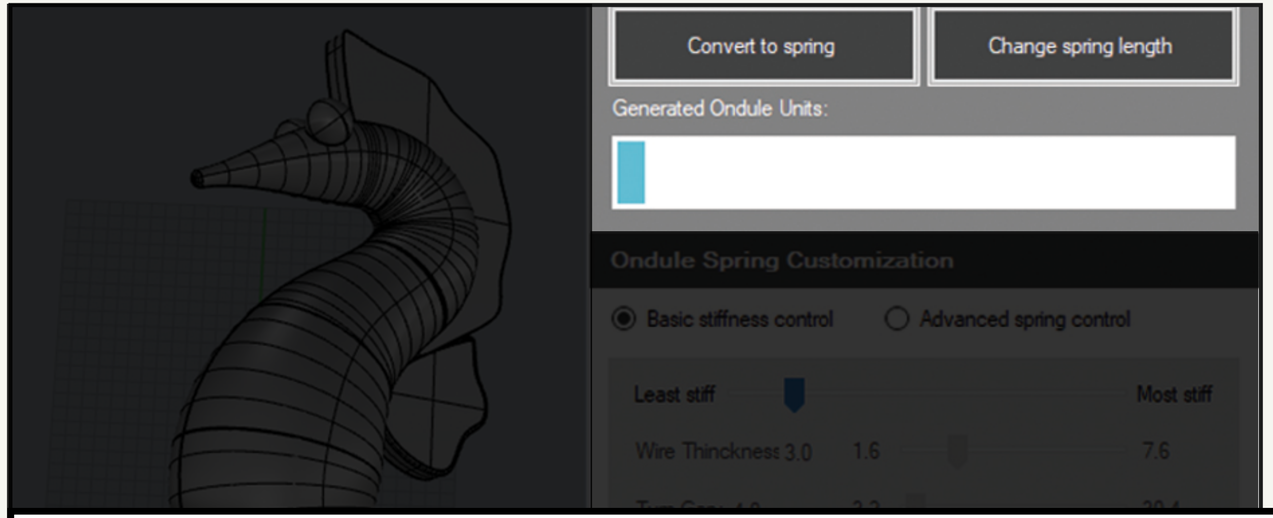


Generate the medial axis

Calculate the size

Ondulé Design Tool

Spring Generation



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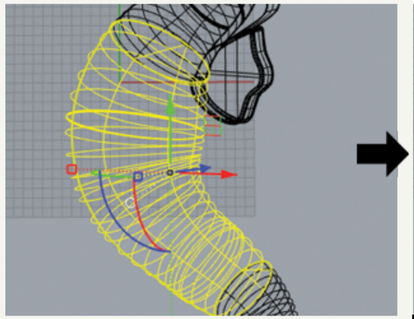

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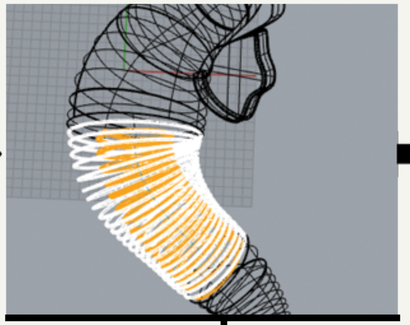
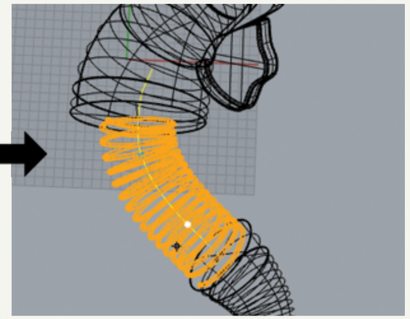
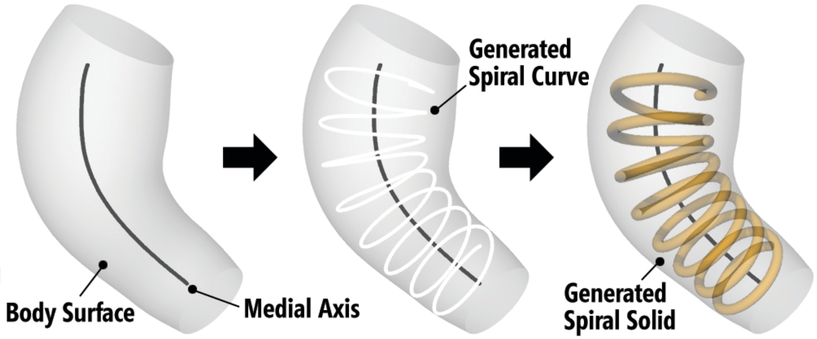


3. Spring Length Change





Generate the medial axis

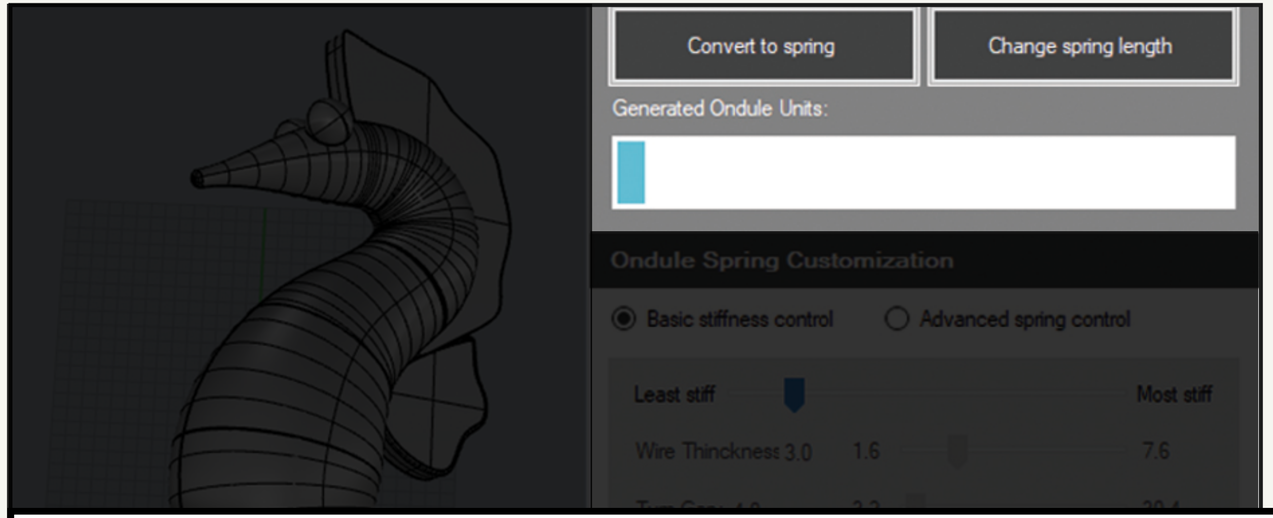
Calculate the size

Generate a spiral

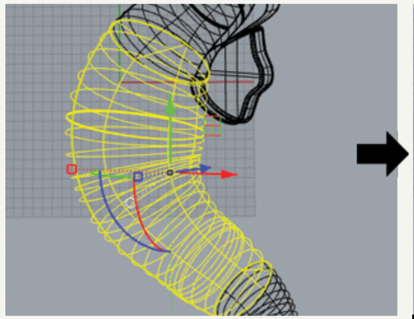
Create the deformation spring

Ondulé Design Tool

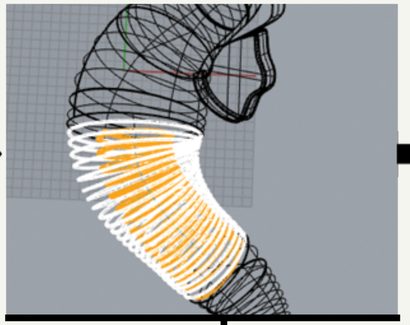
Spring Generation



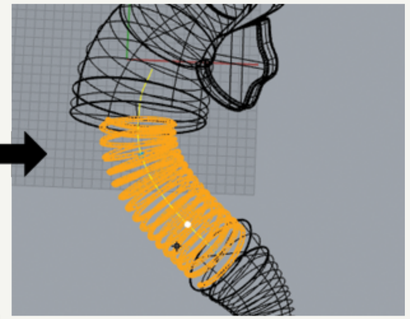
1. Body Selection

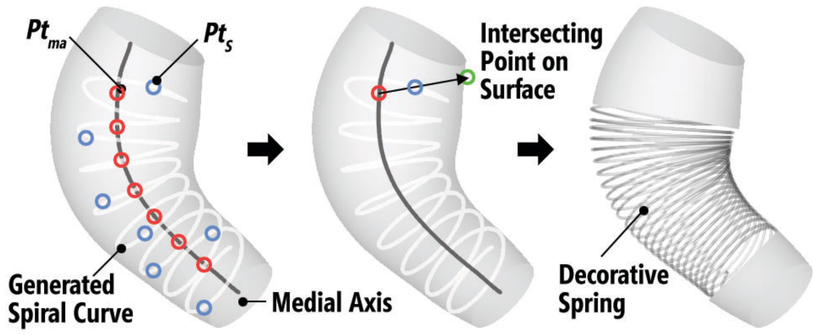


2. Spring Generation



3. Spring Length Change

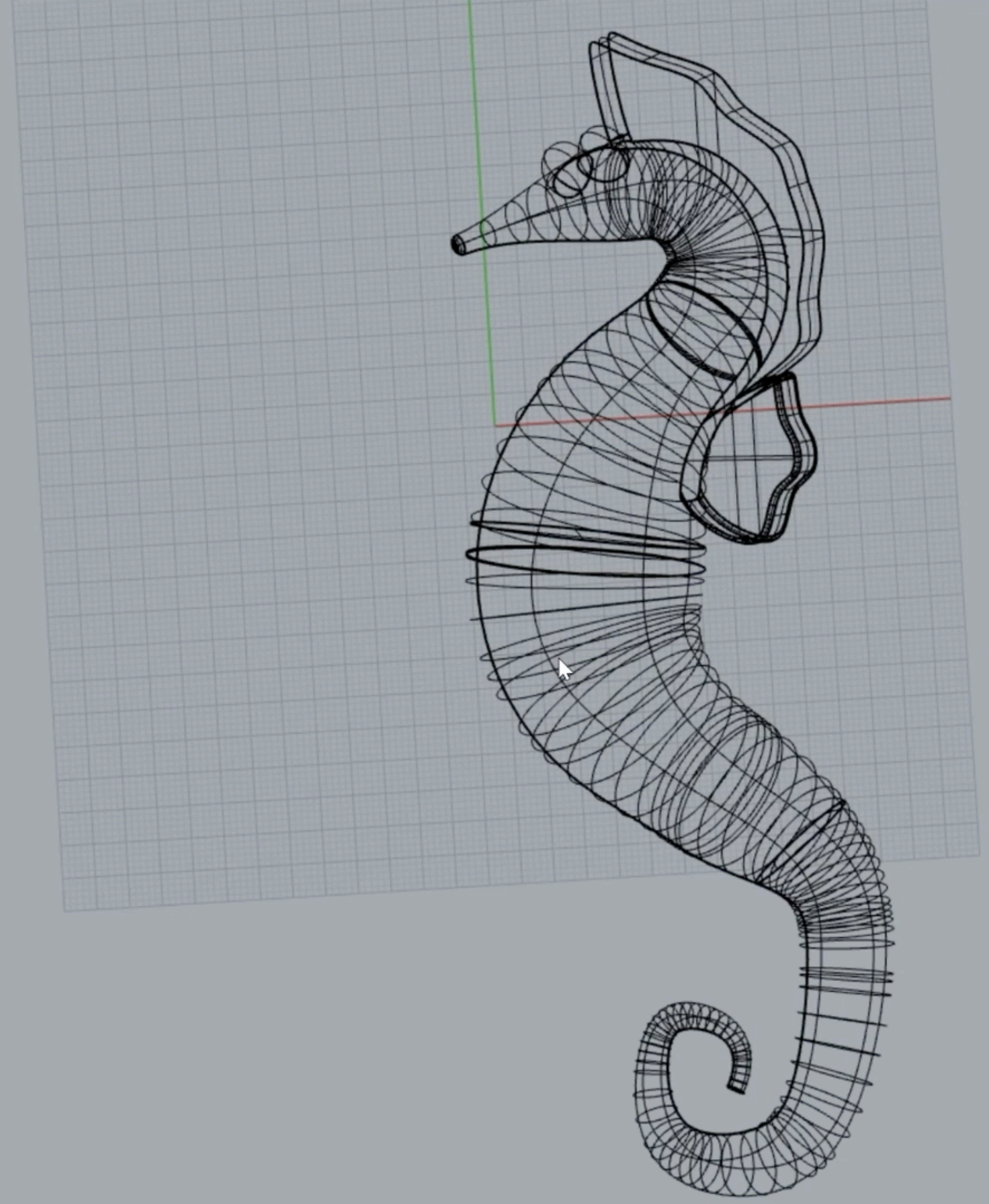




Generate the medial axis
Calculate the size

Generate a spiral
Create the deformation spring

Ray-tracing to find a spiral
Create the decorative spring



Convert to spring | Change spring length

Generated Ondule Units:

Ondule Spring Customization

- (•) Basic stiffness control
- ( ) Advanced spring control

Least stiff			Most stiff
Wire Thinckness	1.6mm	1.6	7.6
Turn Gap:	0.4mm	0.4	100

[ ] Ondule Joint Constraints

Individual Behavior

- ( ) Linear Only
- ( ) Twist Only
- ( ) Bend Only

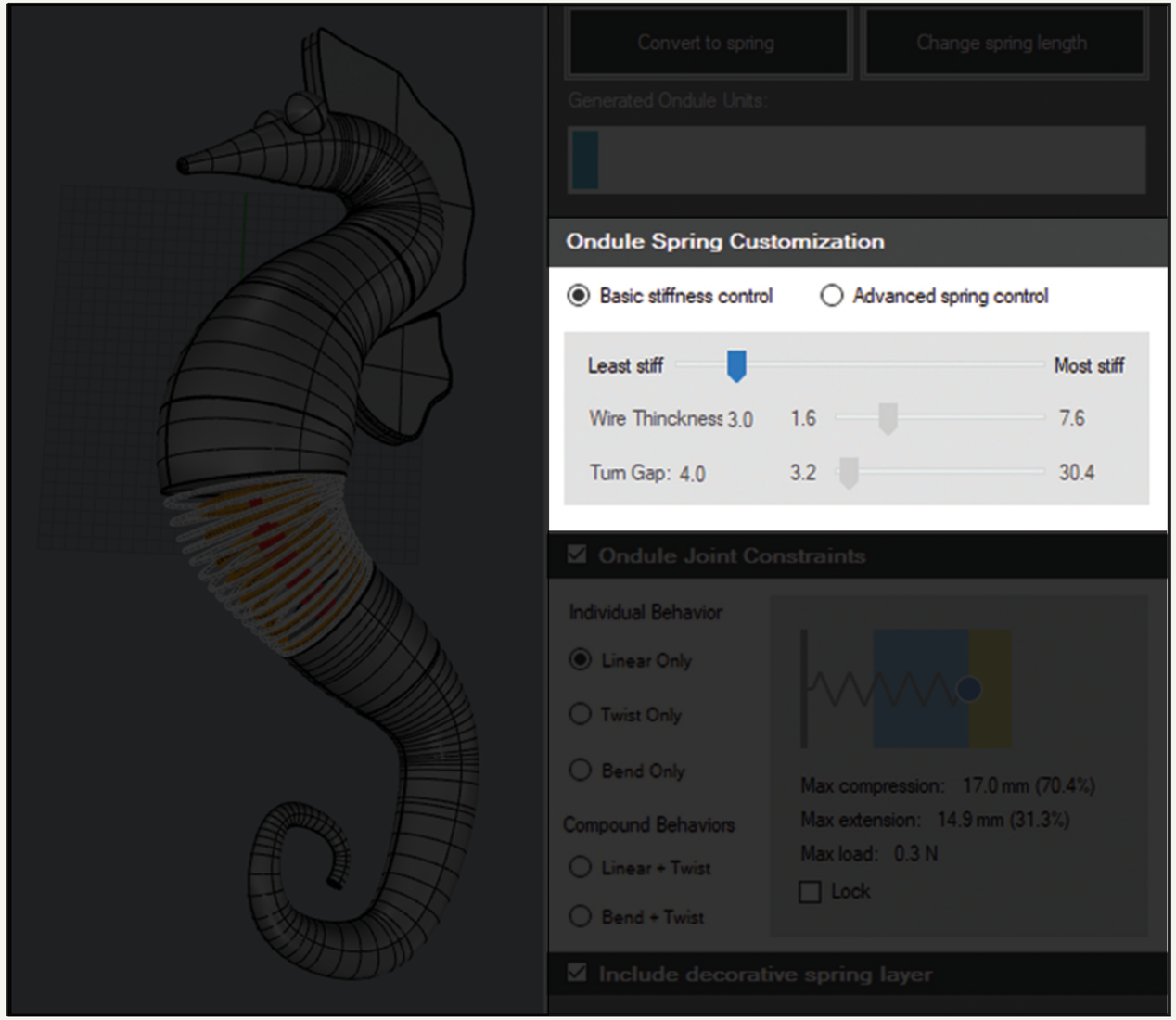
Compound Behaviors

- ( ) Linear + Twist
- ( ) Bend + Twist

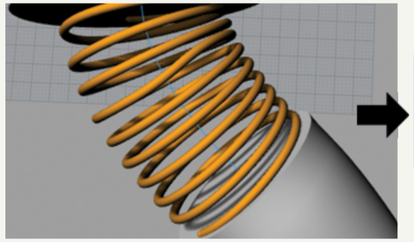
[ ] Include decorative spring layer

Ondulé Design Tool

Spring Stiffness Control

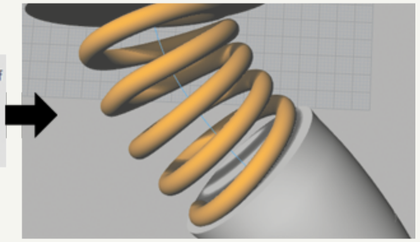


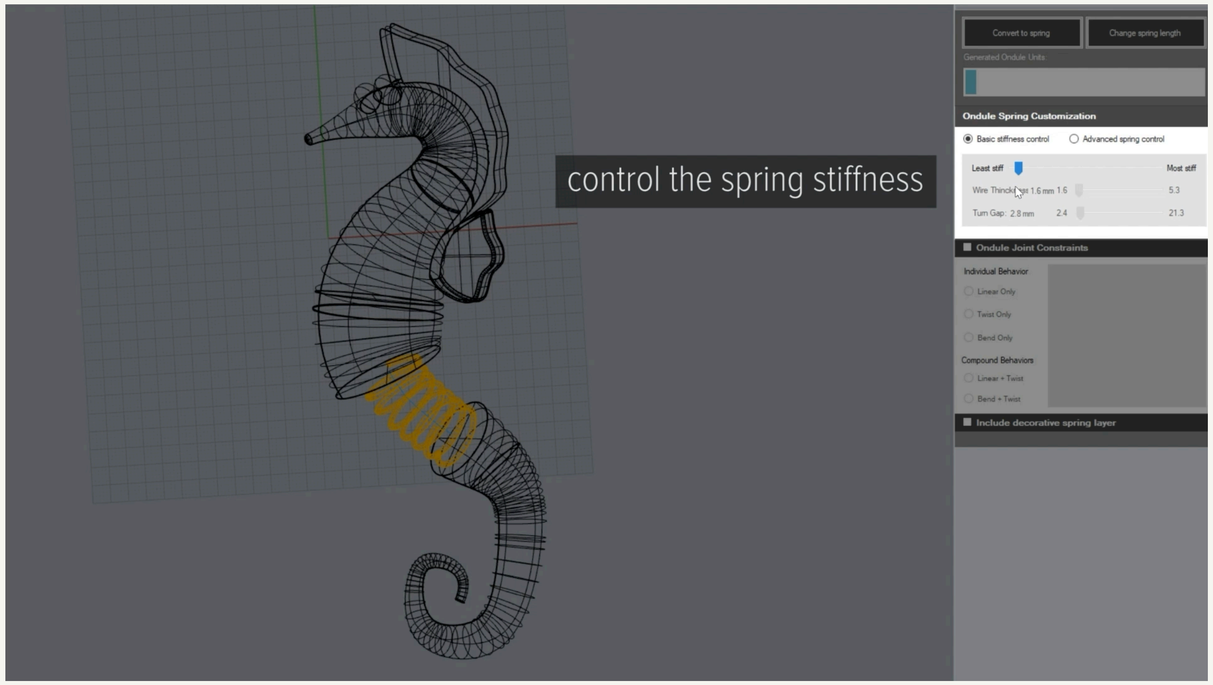
1. Default Stiffness



2. Stiffness Adjustment

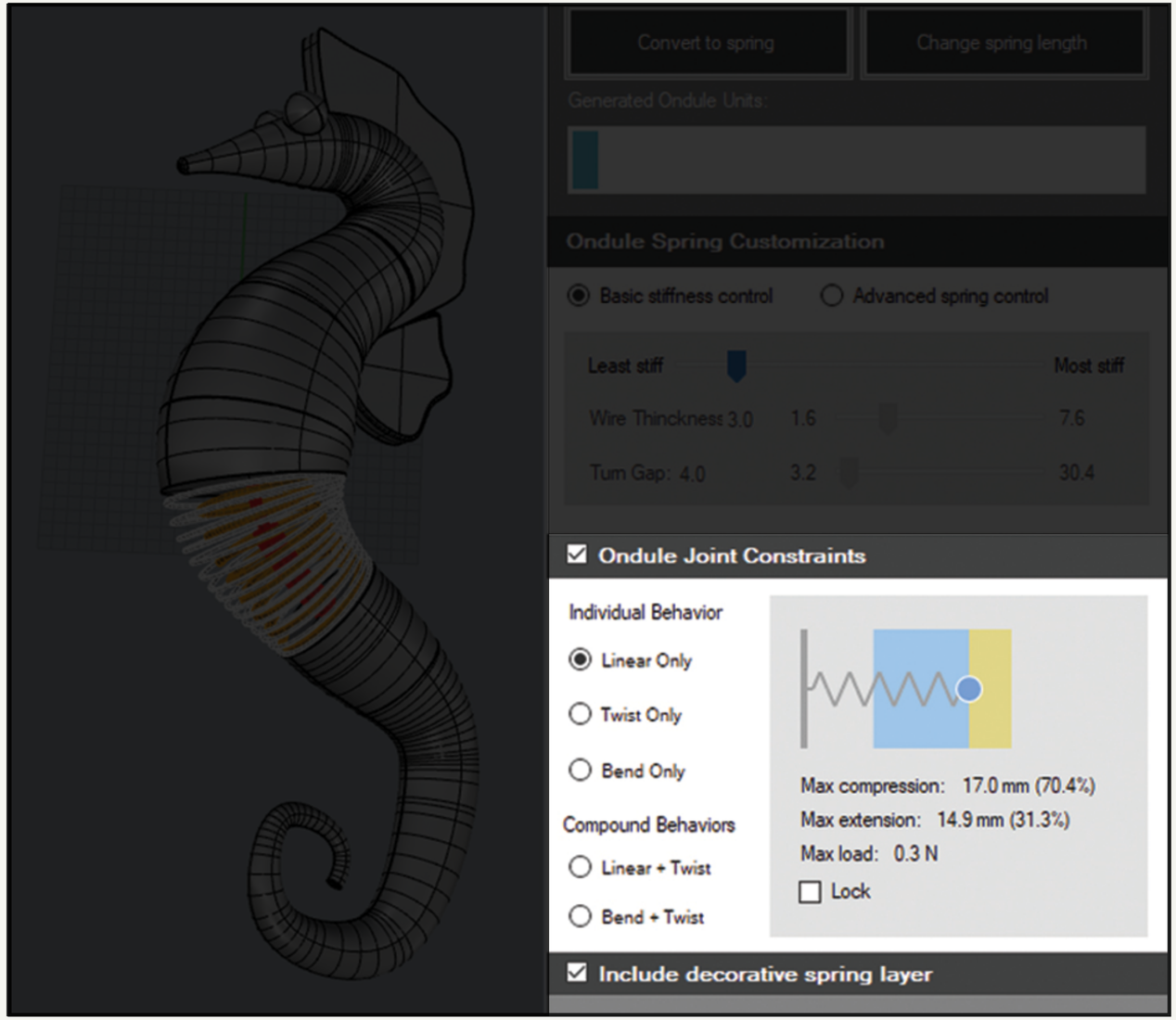
3. Spring Update



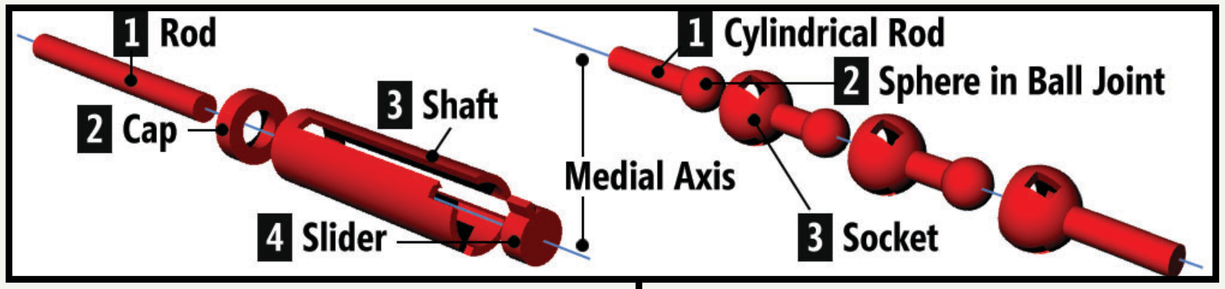


Ondulé Design Tool

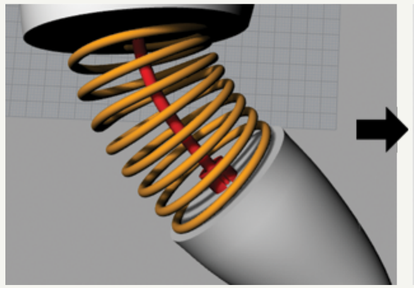
Spring Deformation Behavior Design



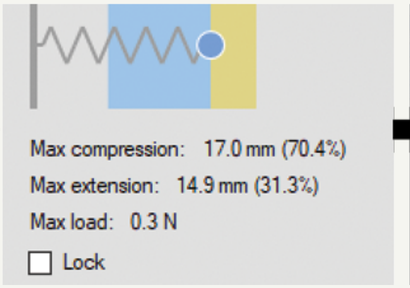
Joint Generation



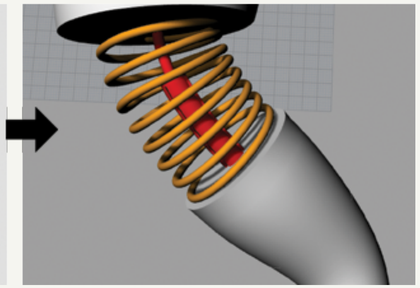
1. Default Joint Design



2. Behavior Design



3. Joint Update



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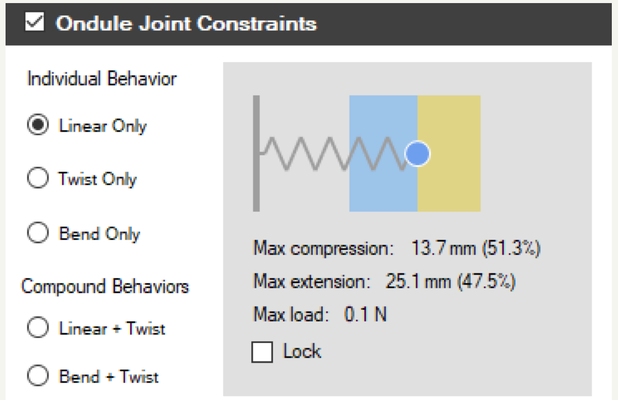
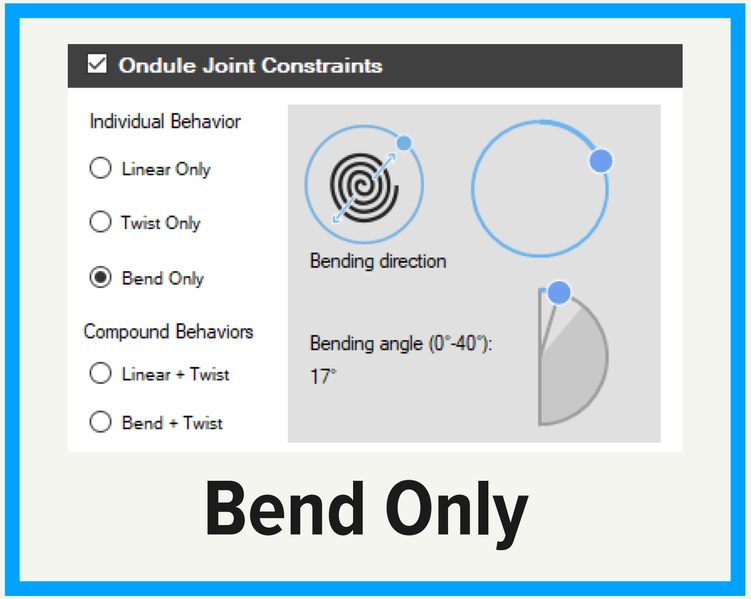
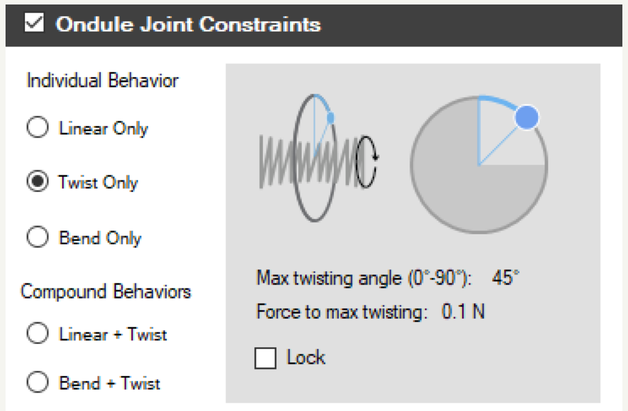


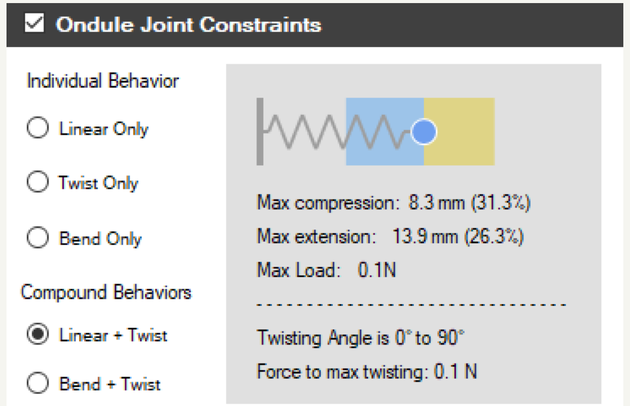
Linear Only



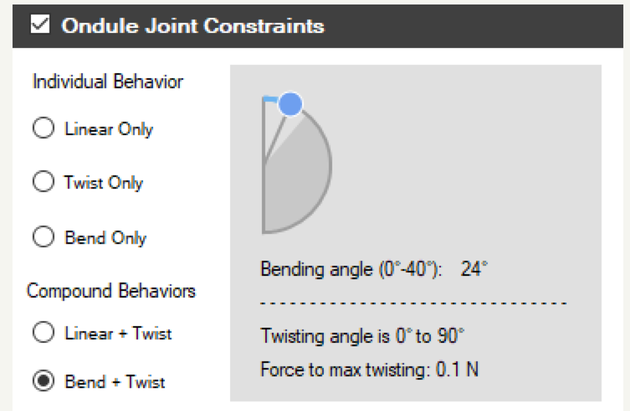
Bend Only



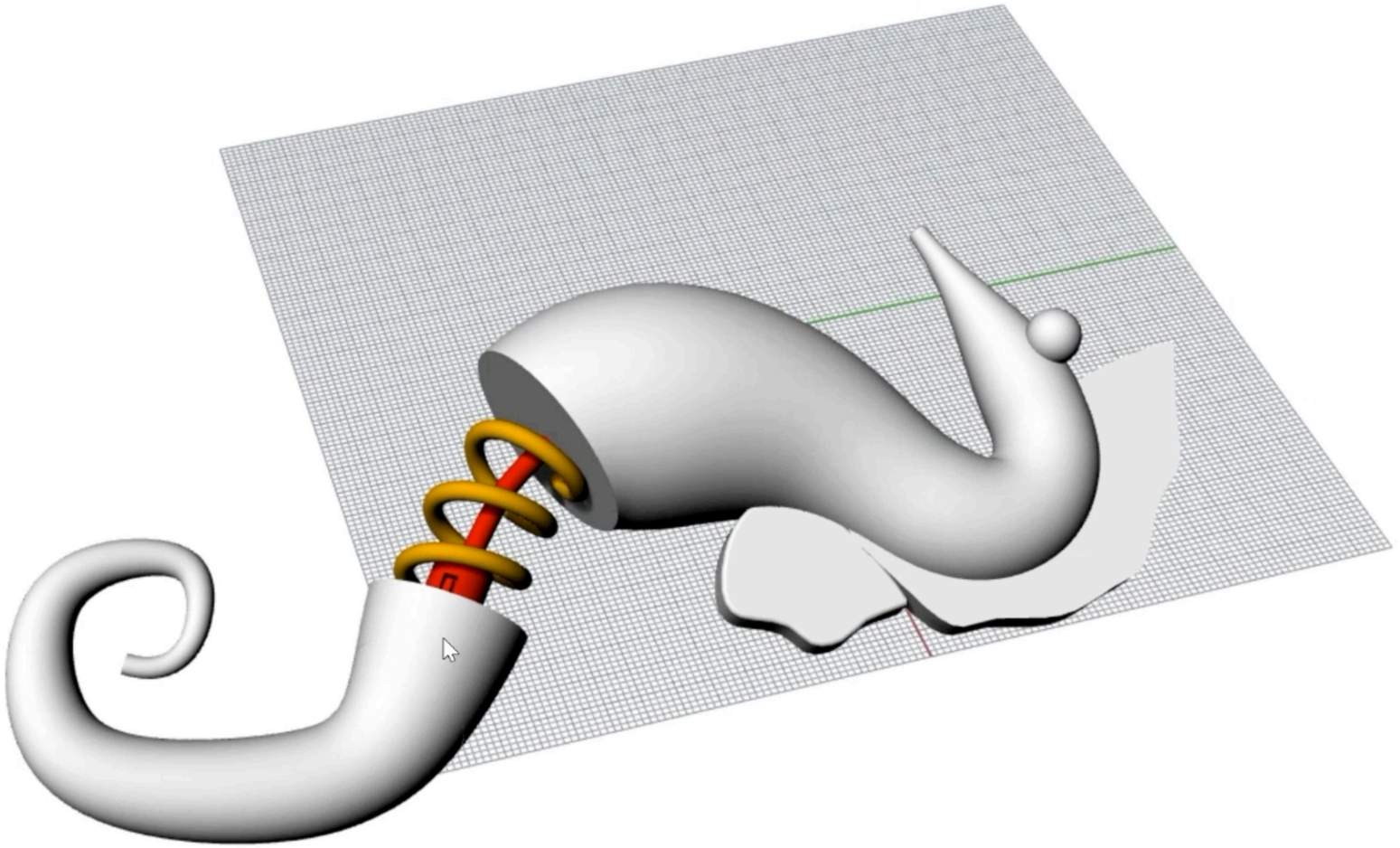
Twist Only



Linear + Twist



Bend + Twist



4X

Convert to spring | Change spring length

Generated Ondule Units:

Ondule Spring Customization

- ○ Basic stiffness control
- ◉ Advanced spring control

Least stiff — Most stiff

Wire Thinckness	2.9 mm	1.6	5.3
Turn Gap:	6.8	2.4	21.3

☑ Ondule Joint Constraints

Individual Behavior

- ◉ Linear Only
- ○ Twist Only
- ○ Bend Only

Compound Behaviors

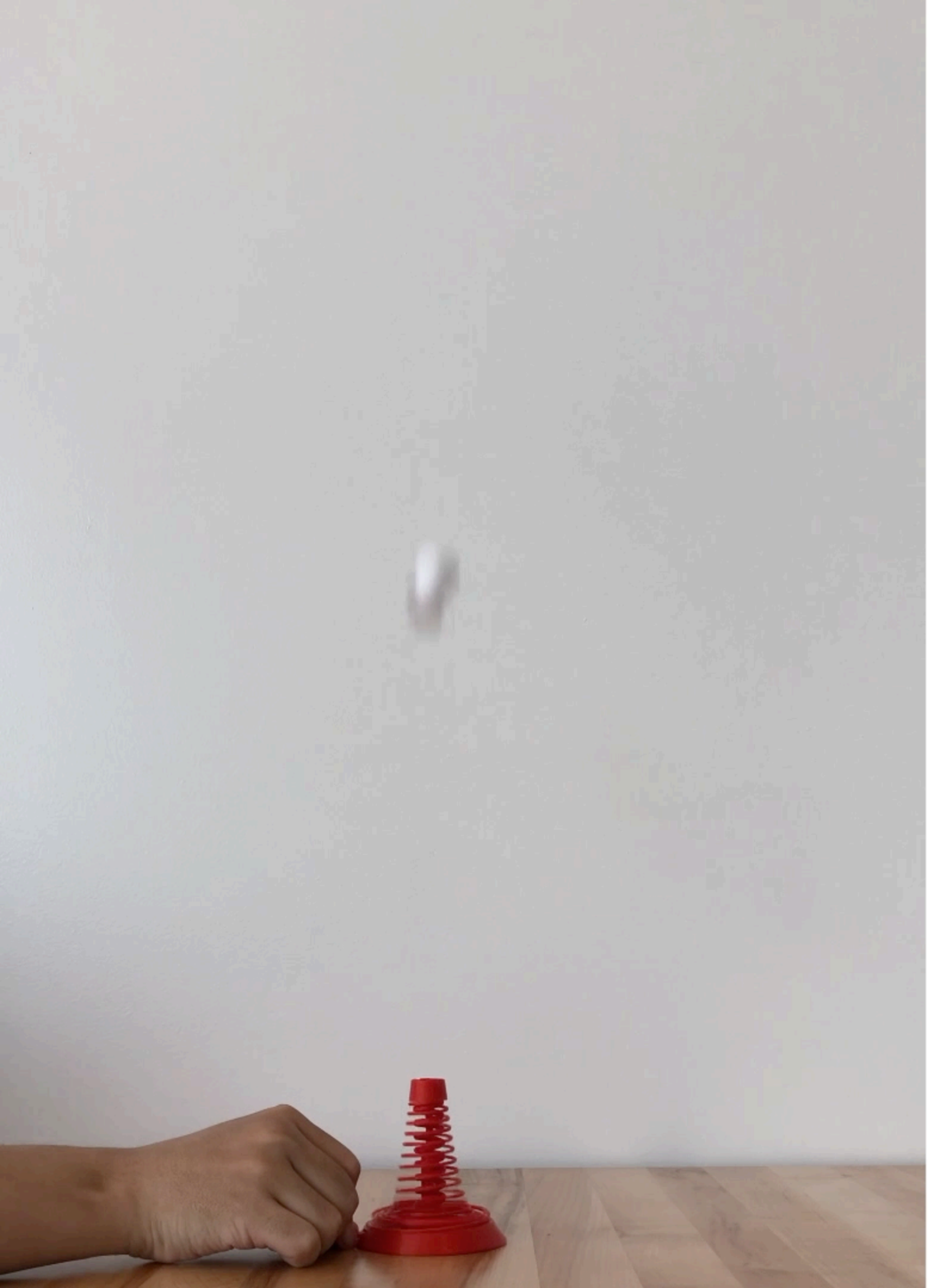
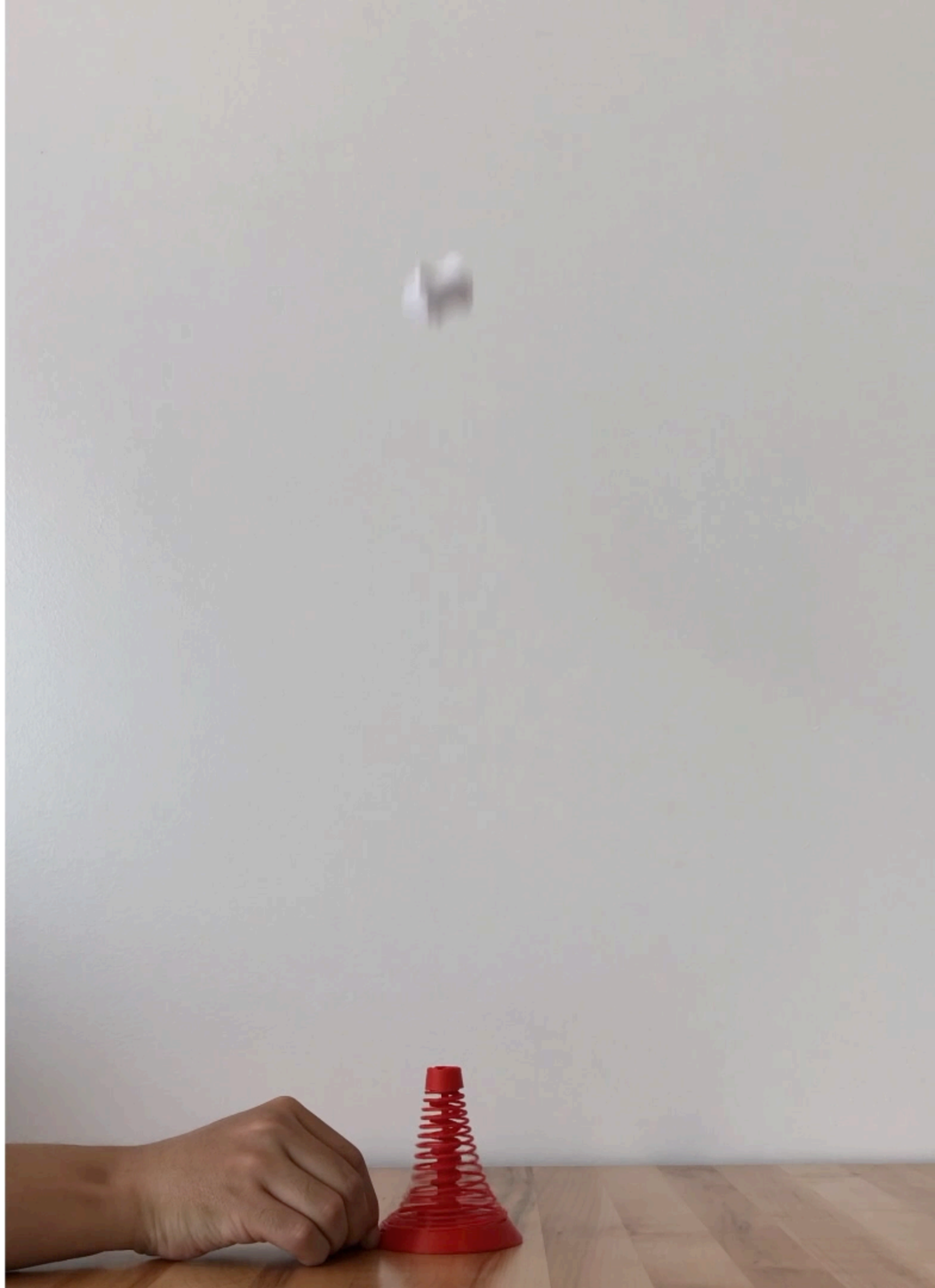
- ○ Linear + Twist
- ○ Bend + Twist

Max compression: 0.6 mm (5.1%)
Max extension: 0.6 mm (2.6%)
Max load: 0.4 N
☐ Lock

☐ Include decorative spring layer

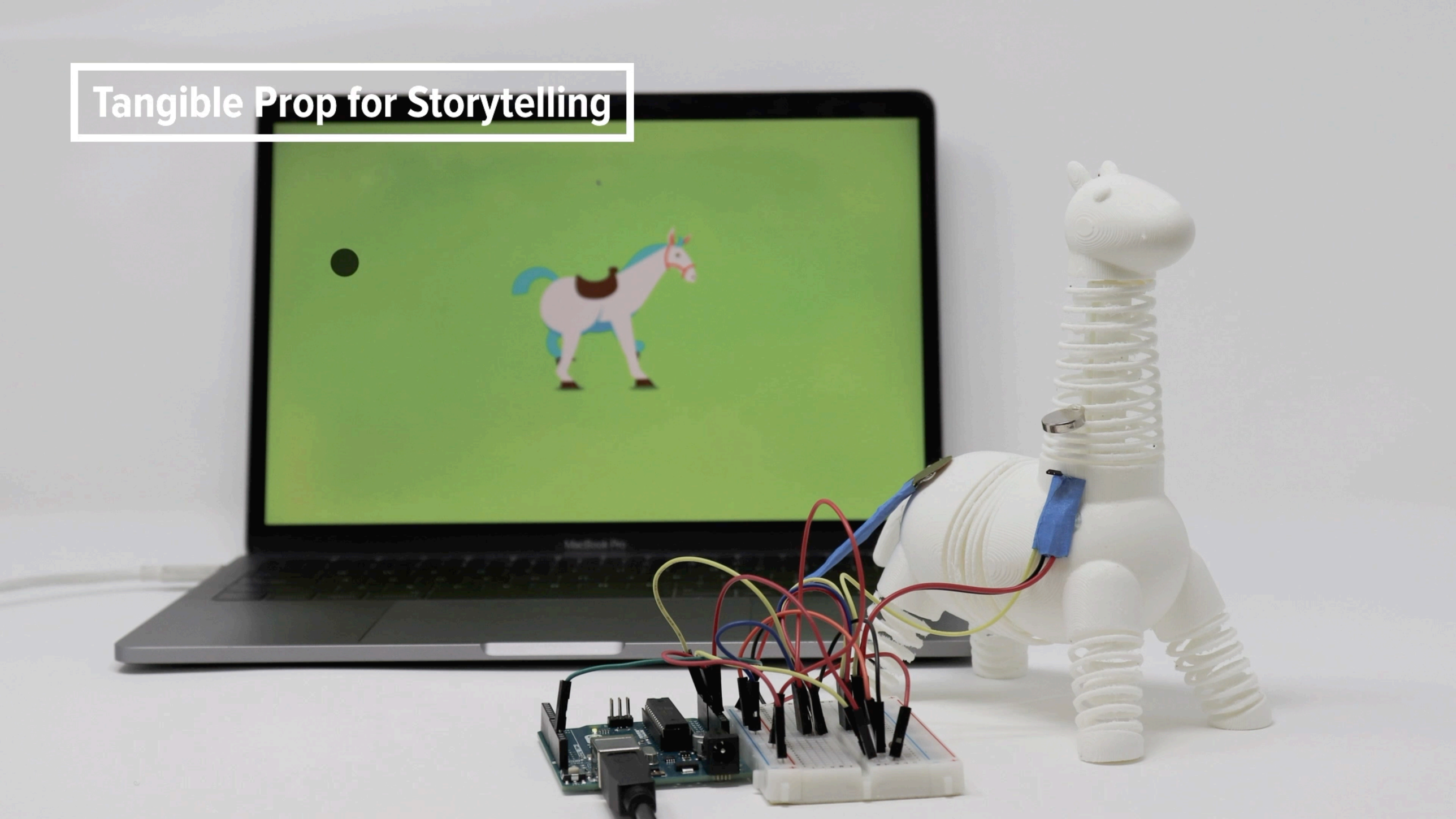
Ondulé Applications

Jack-in-the-box

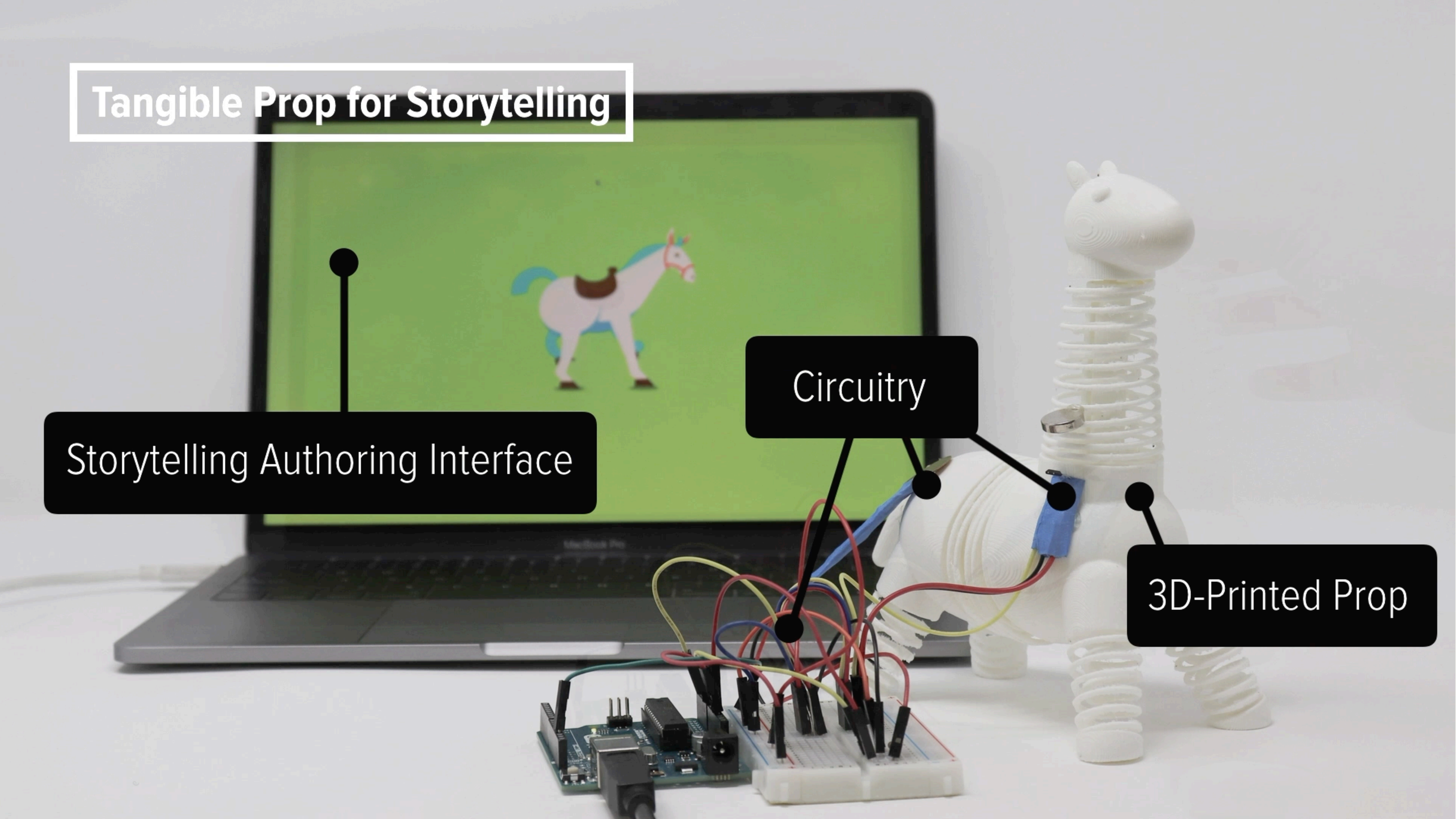




MEDIUM TENSION
GRIP MASTER
prohands

Tangible Prop for Storytelling

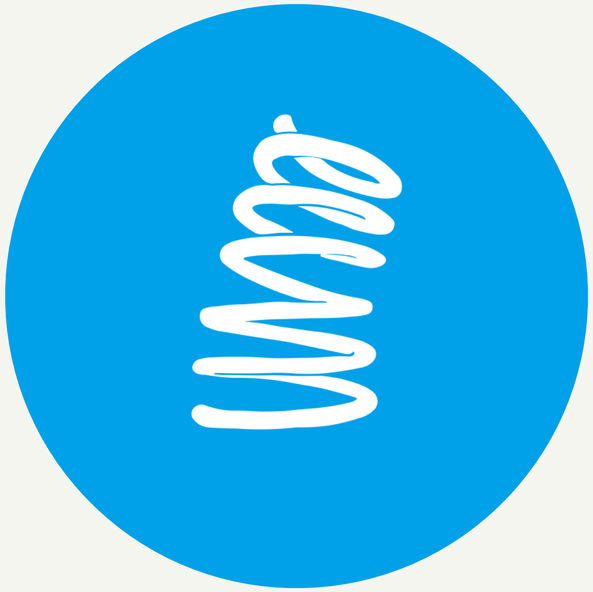


Tangible Prop for Storytelling

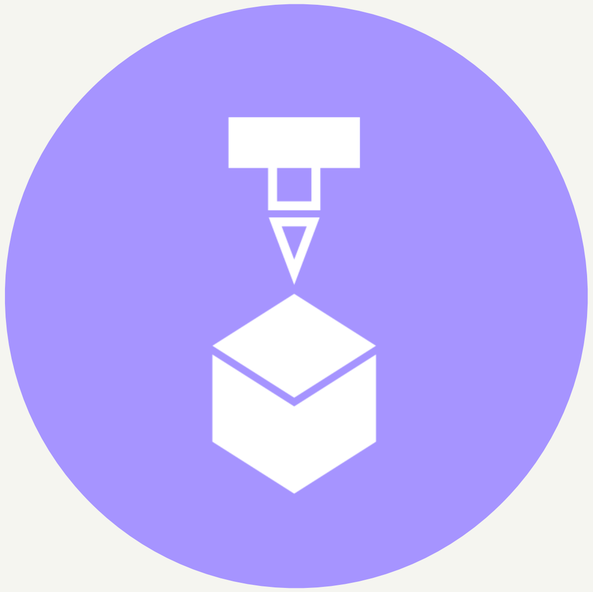



Accessible Cutting Device

Future Work



Geometry Constraints



Spring Robustness

Simulation

Summary

A new approach to allow novices to convert a static 3D shape into a deformable object with embedded 3D-printed springs and joints.

Conducted mechanical experiments
Proposed a set of deformation techniques using springs and joints
Developed a design tool
Built a set of example applications supported by Ondulé

Acknowledgment

William F Kuykendall / Joshua Land / Mark Fuge / Ruofei Du /Sophie Tian
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Ondulé: Designing and Controlling 3D Printable Springs


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Thank you! Questions?