Investigation of the Mechanical Behavior of Locking Chains

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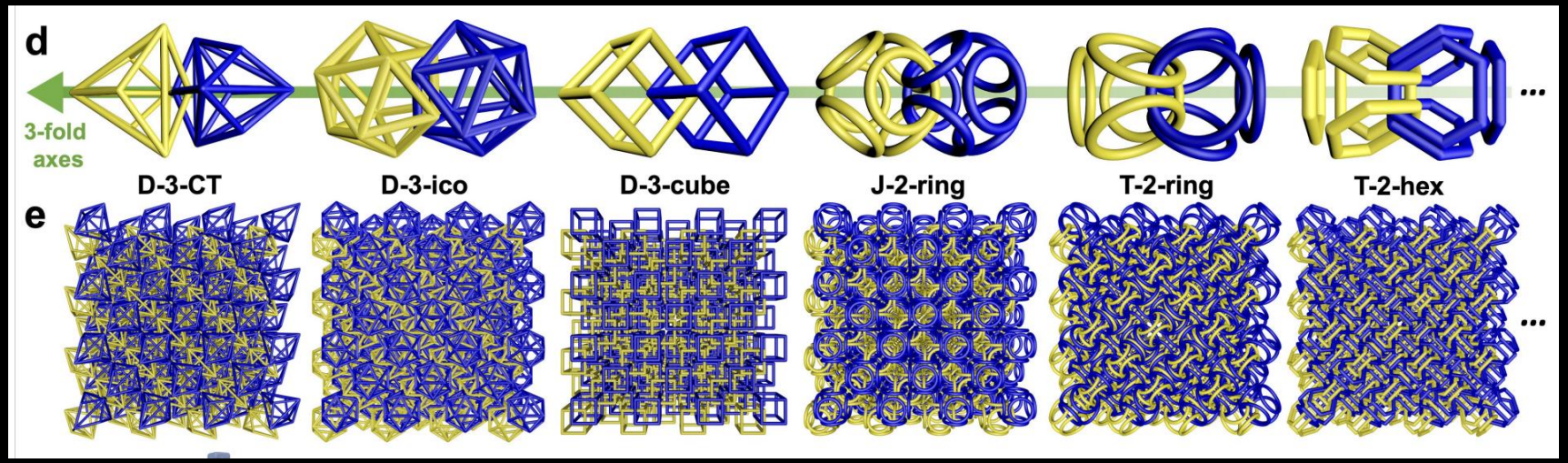
Daraio Research Group

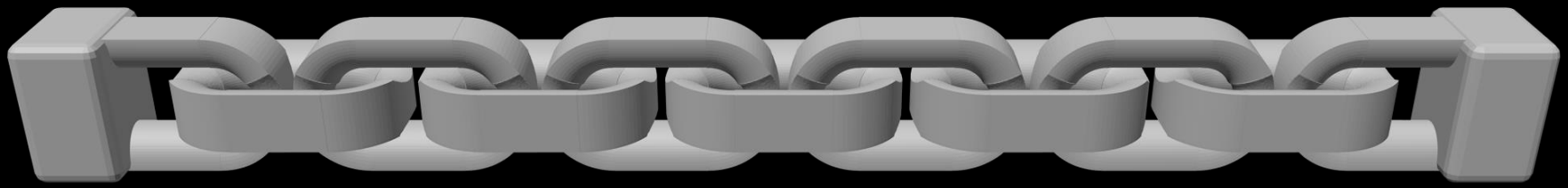
Caltech

Polycatenated Architected Materials (PAMs)

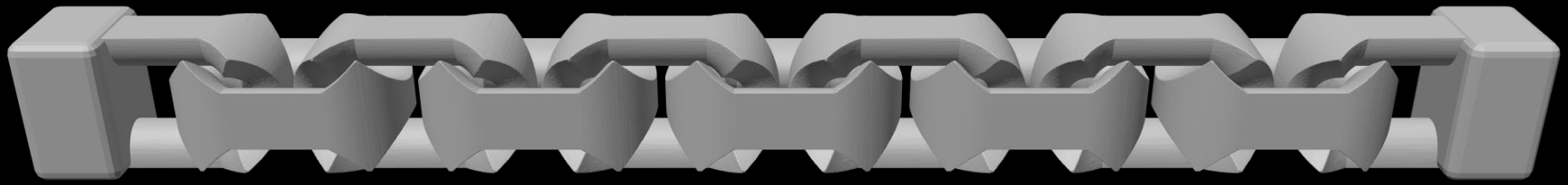
- Topologically interlinked particles
- Modify behavior of PAMs by changing the particles' geometry



Non-Locking Chain

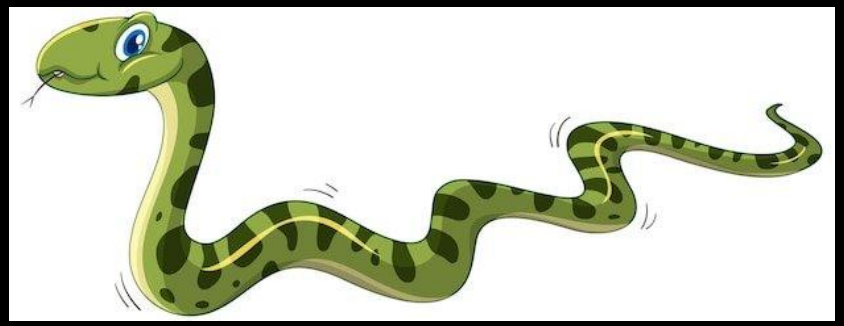


Locking Chain



Applications

Unlocked



Locked

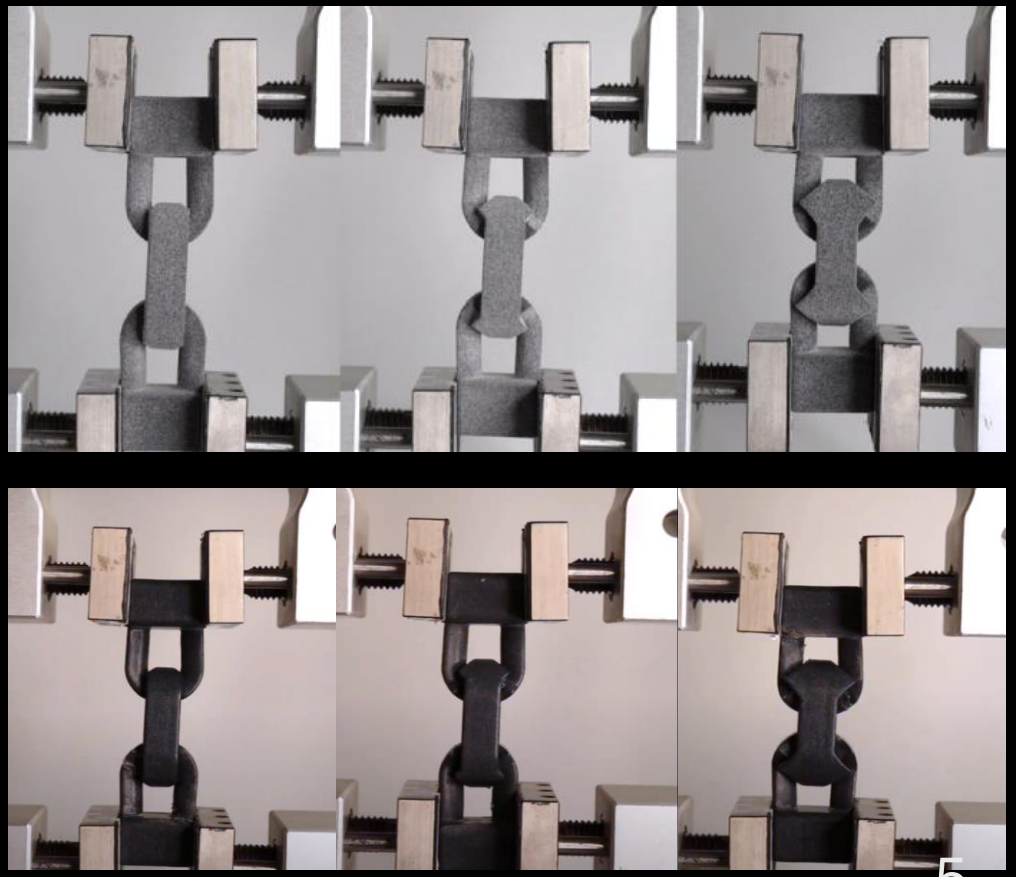
What to Study?

- Tunability of locking mechanism
- Friction
- Loading Rate

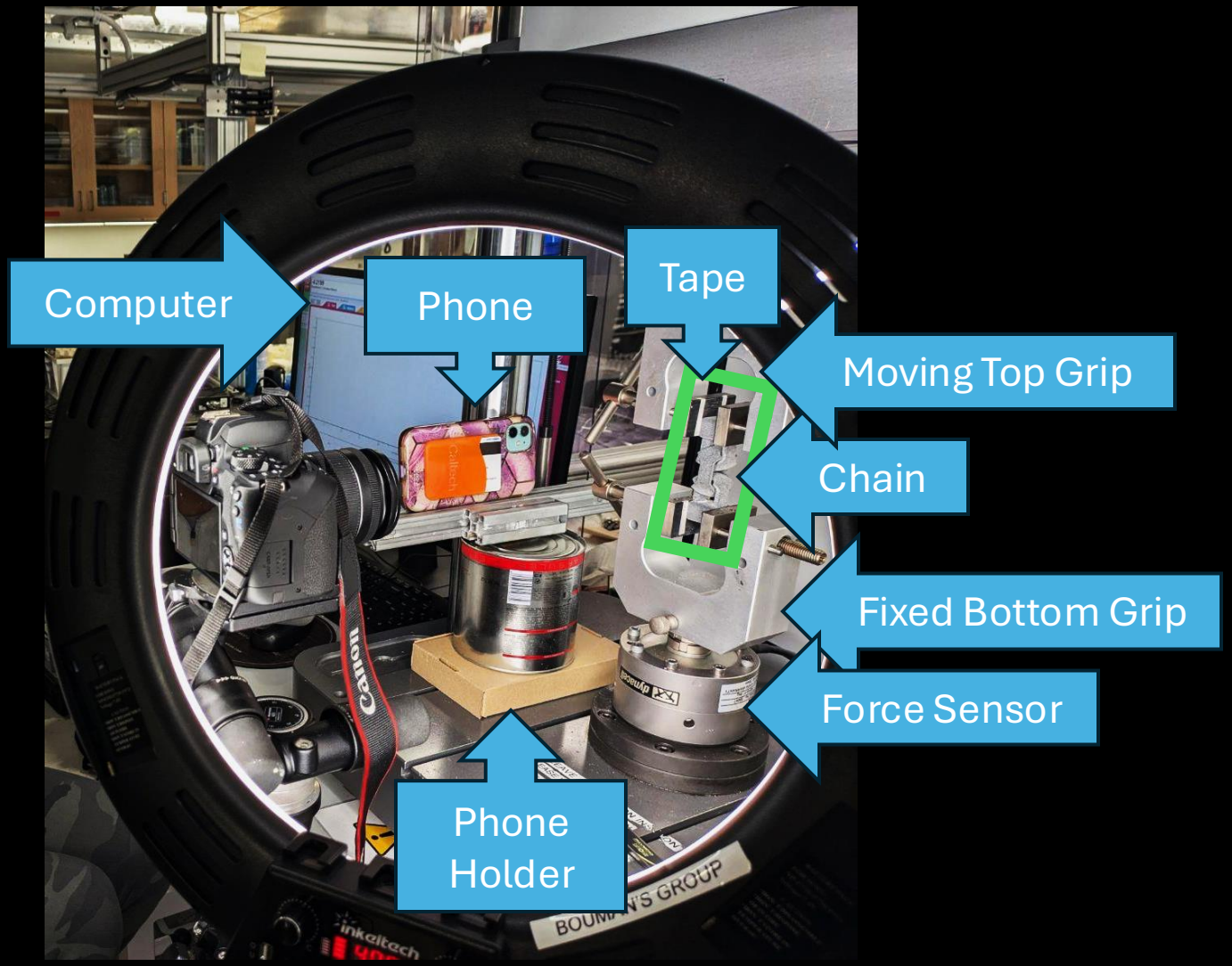
Non-locking | Quasi-locking | Locking

Light: Rough surface

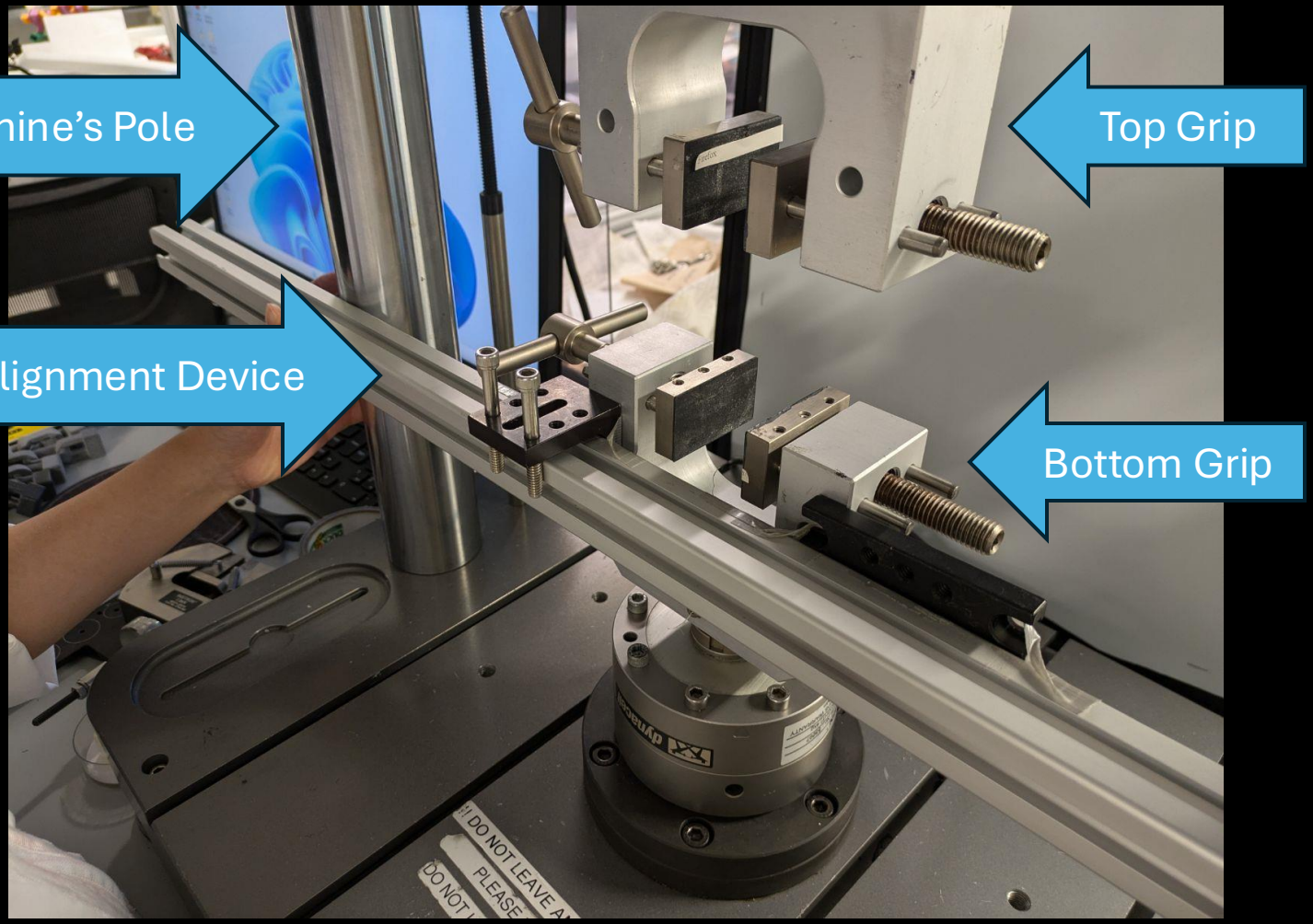
Dark: Smooth surface



Experimental Set-up for 3-Particle Chains on the Instron ElectroPuls 3000

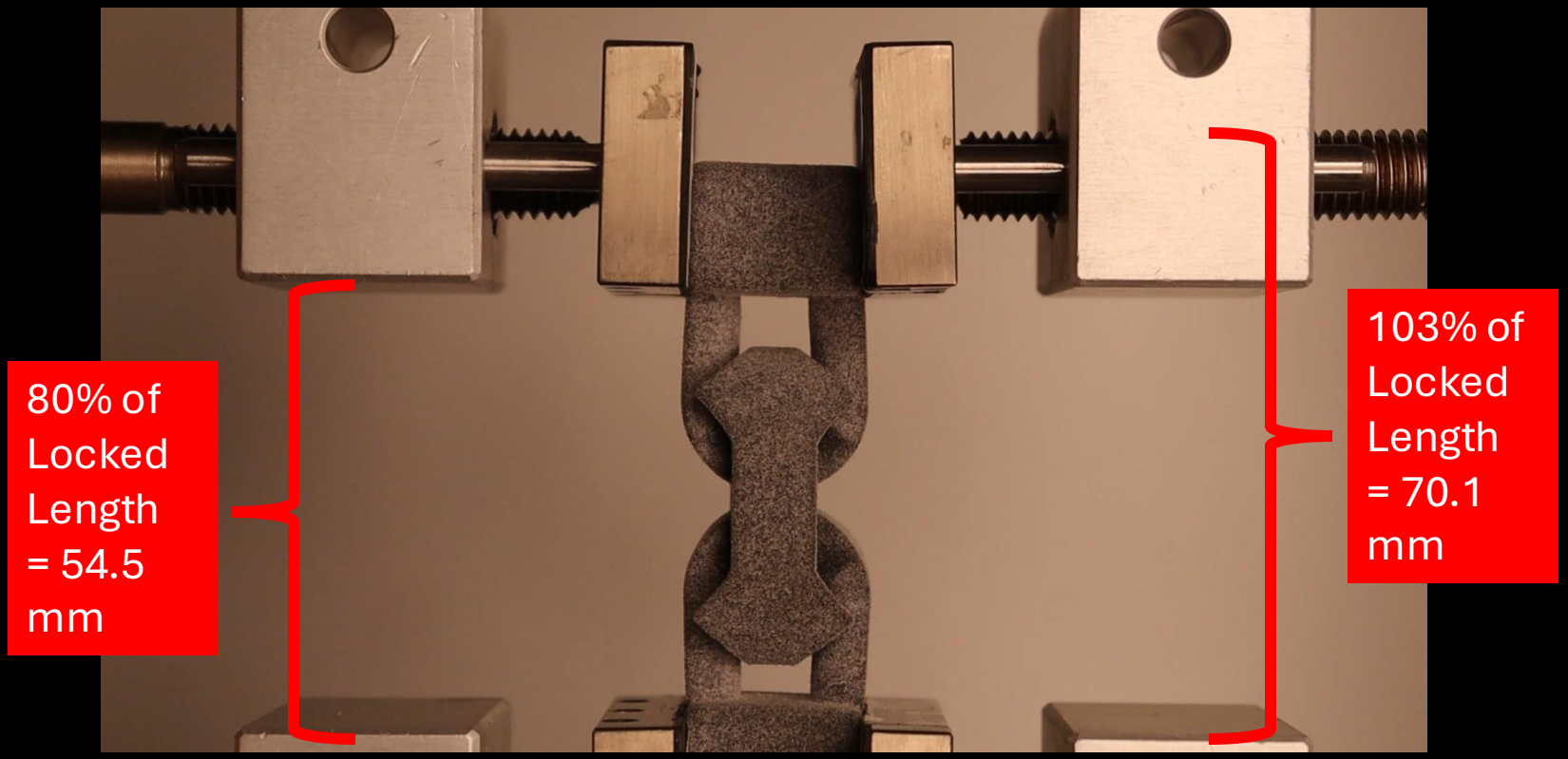


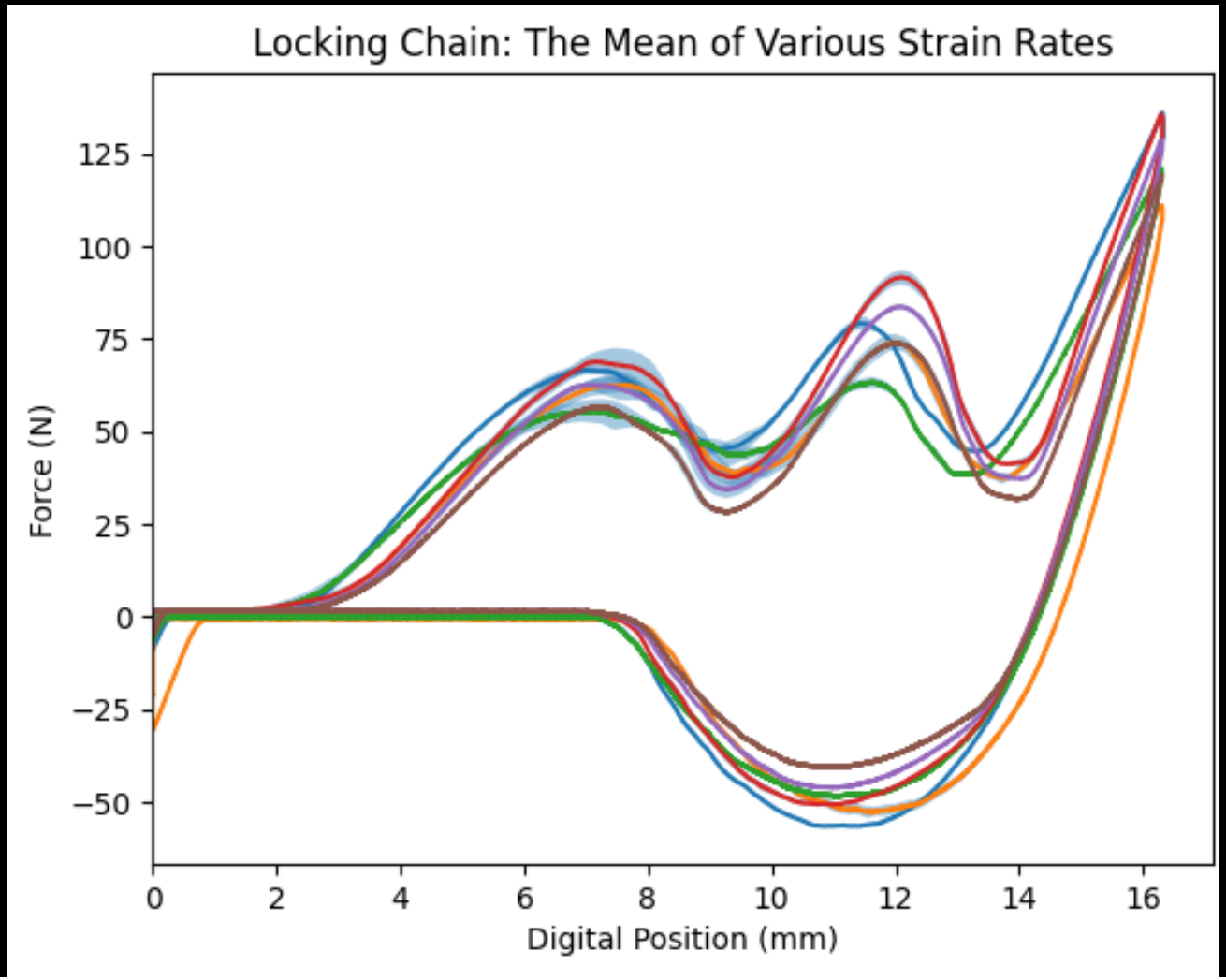
Aligning the Grips



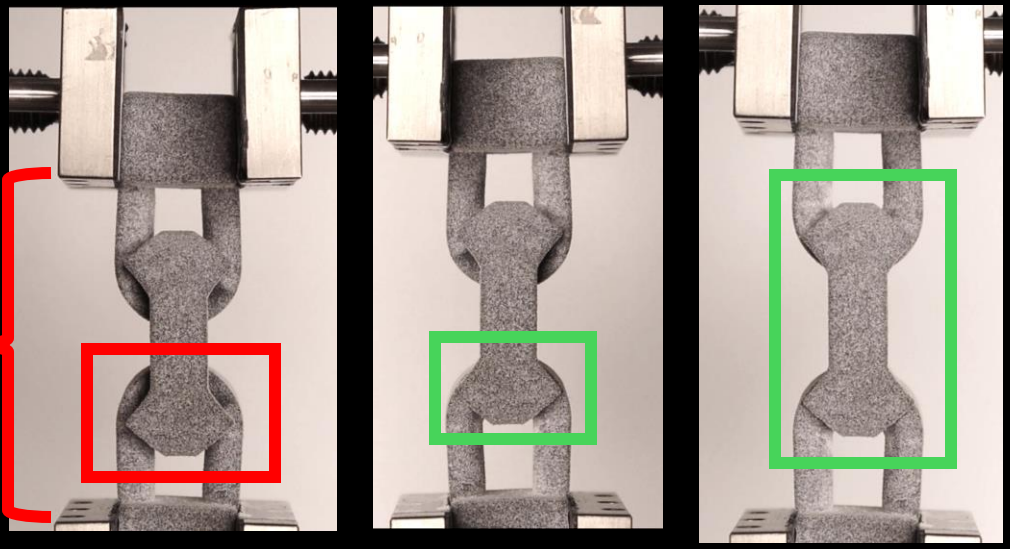
Three-Particle Chain

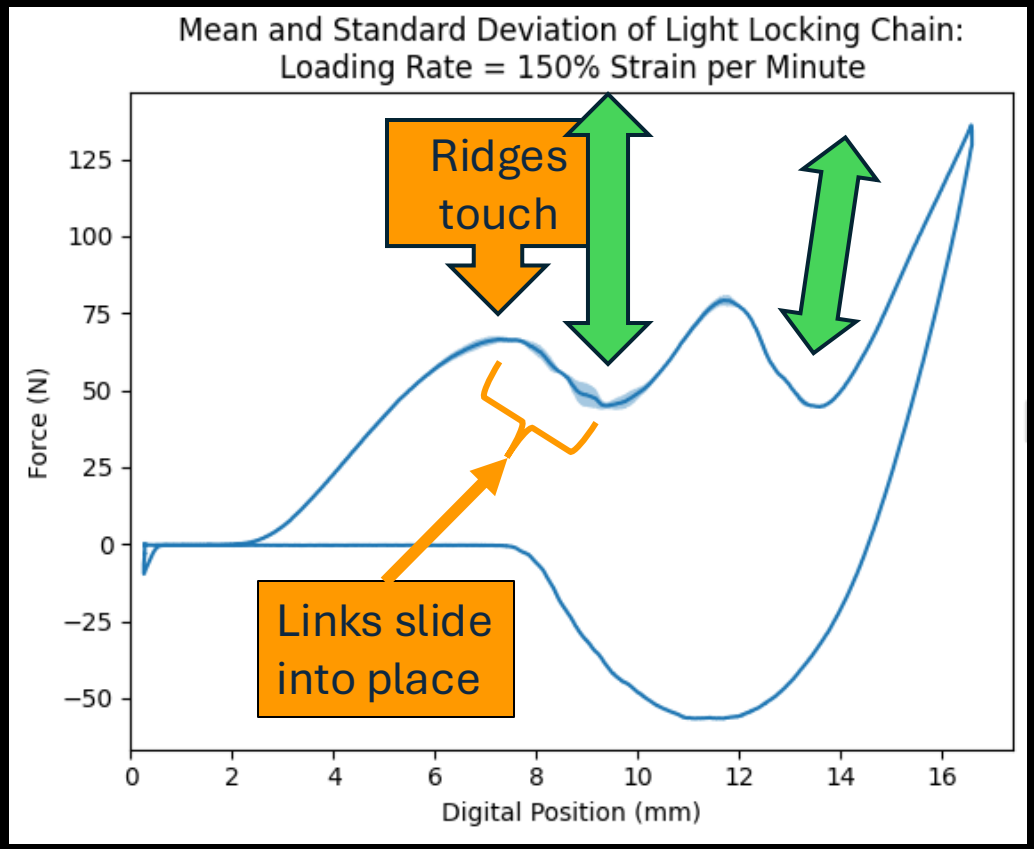
- Strain = (How much chain is stretched) / (Initial Length)
- Loading rates: 10%, 50%, 150% strain per minute
- Three trials per rate and chain



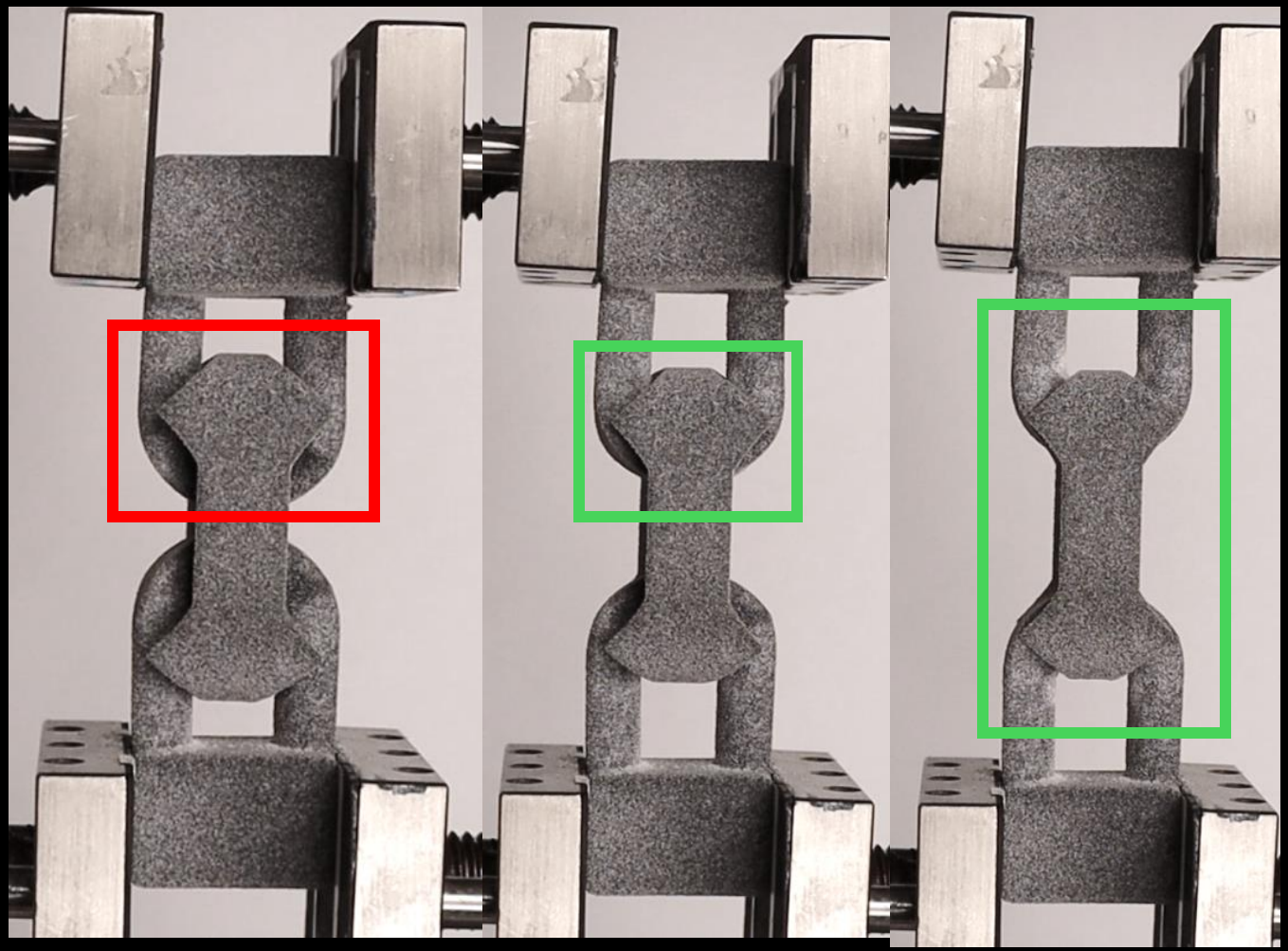

Locking Chain: The Mean of Various Strain Rates
Force (N)
125
100
75
50
25
0
−25
−50
0
2
4
6
8
10
12
14
16
Digital Position (mm)
Light Locking Chain: Rate = 150% Strain per Minute, Mean Loading Area: 0.80 N * m
Light Locking Chain: Rate = 50% Strain per Minute, Mean Loading Area: 0.67 N * m
Light Locking Chain: Rate = 10% Strain per Minute, Mean Loading Area: 0.70 N * m
Dark Locking Chain: Rate = 150% Strain per Minute, Mean Loading Area: 0.79 N * m
Dark Locking Chain: Rate = 50% Strain per Minute, Mean Loading Area: 0.71 N * m
Dark Locking Chain: Rate = 10% Strain per Minute, Mean Loading Area: 0.62 N * m

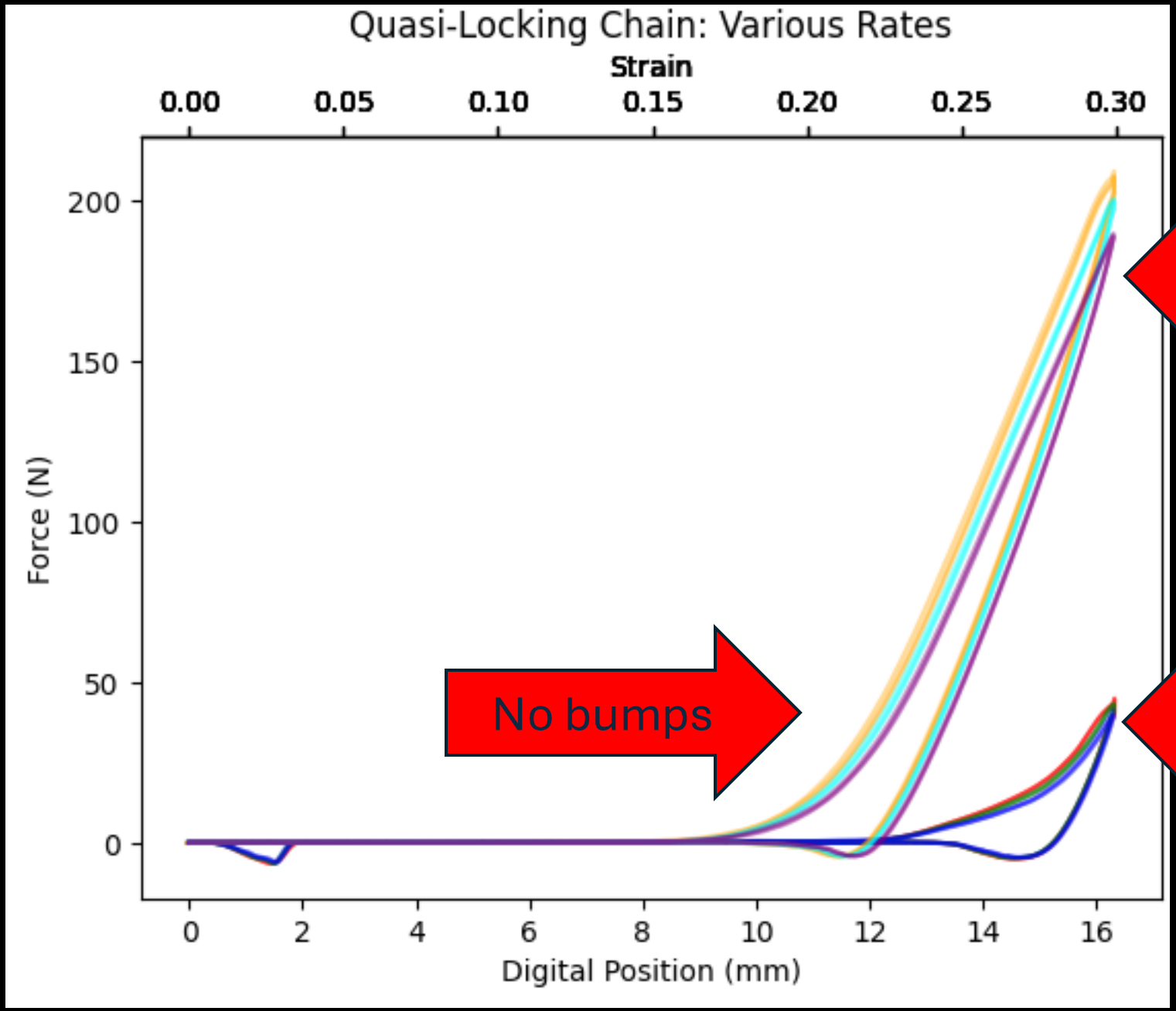
Digital Position = 0 mm

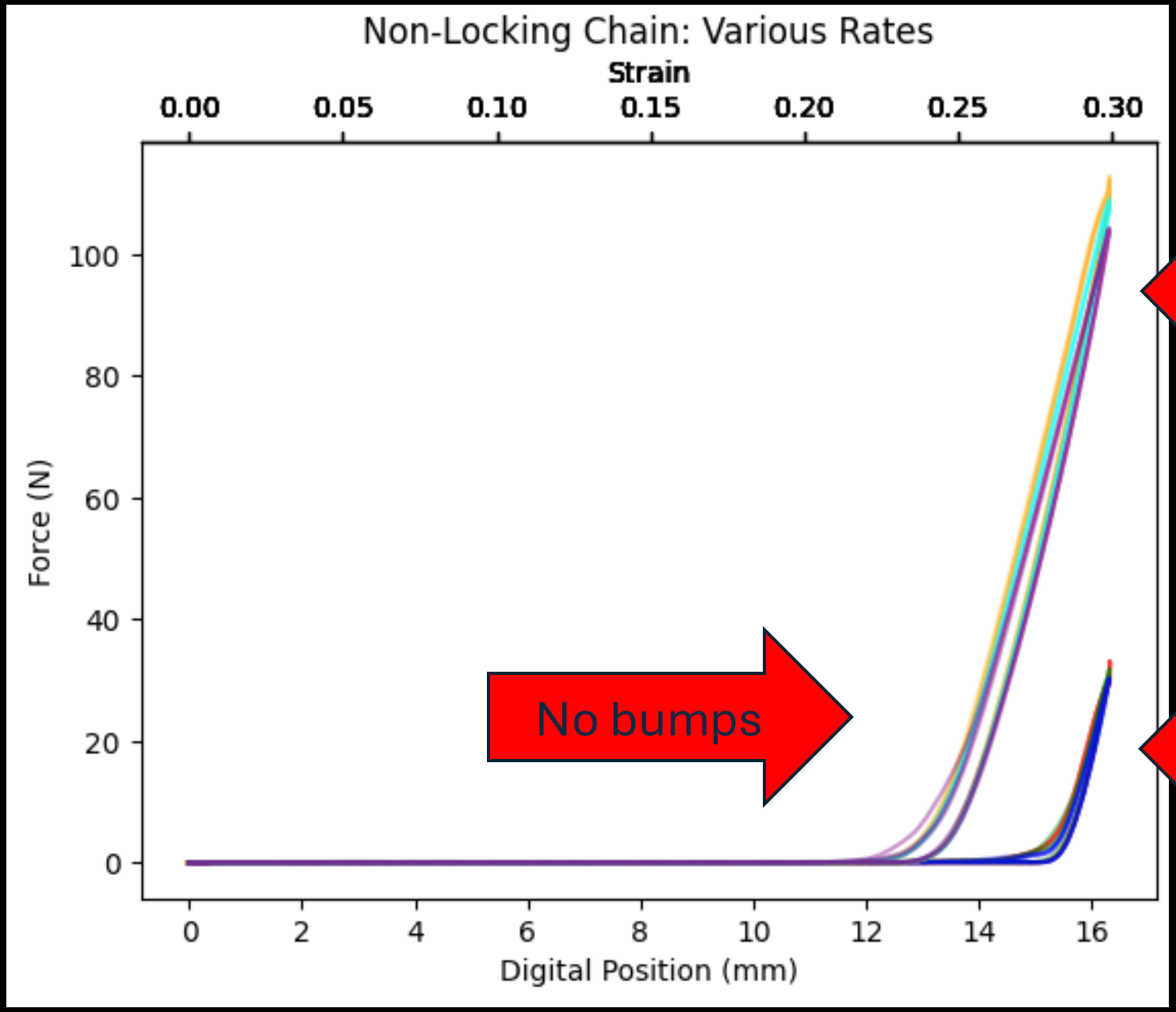


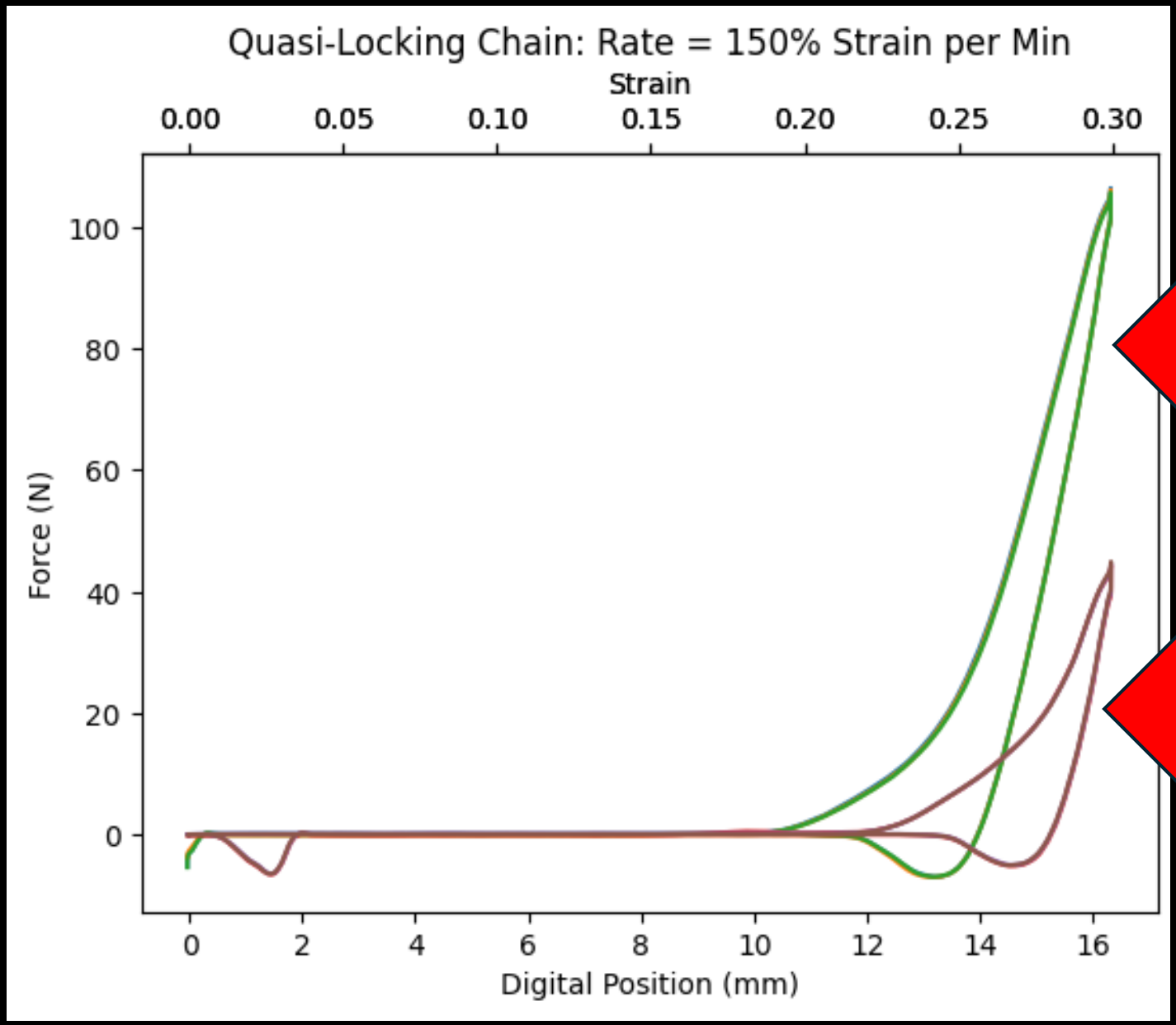


In a future experiment…

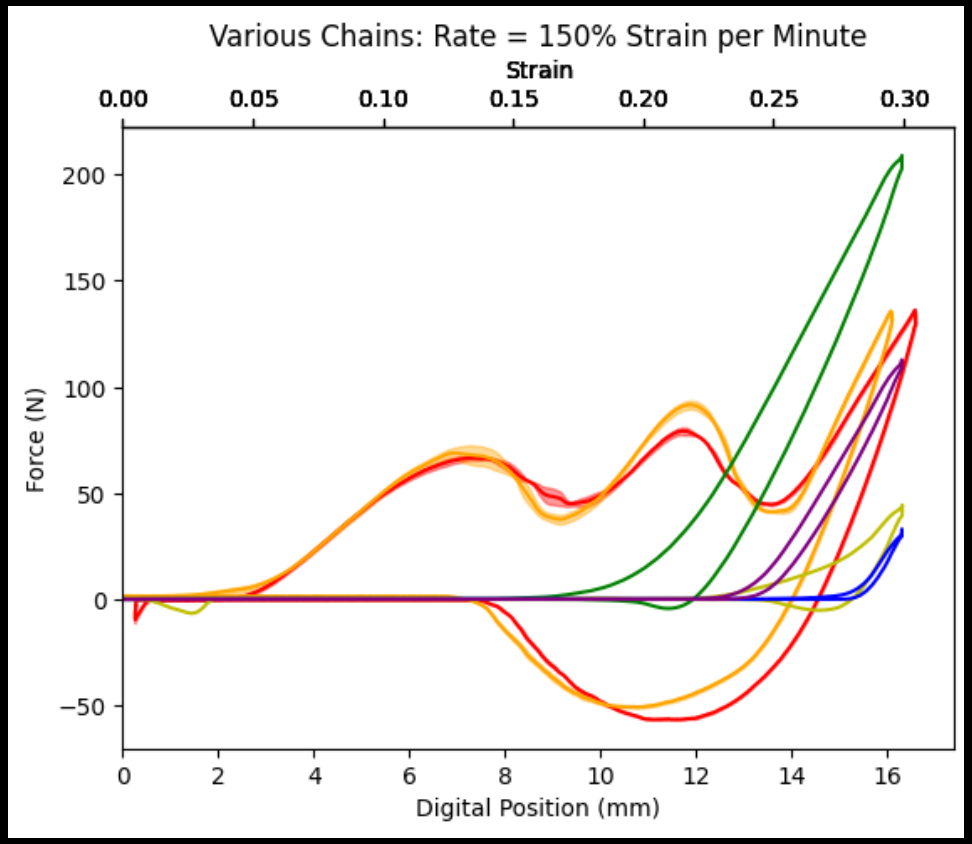



Quasi-Locking Chain: Various Rates
Strain
0.00
0.05
0.10
0.15
0.20
0.25
0.30
200
150
100
50
0
Force (N)
0
2
4
6
8
10
12
14
16
Digital Position (mm)
Dark
No bumps
Light


Non-Locking Chain: Various Rates
Strain
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Force (N)
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
Digital Position (mm)
Dark
No bumps
Light

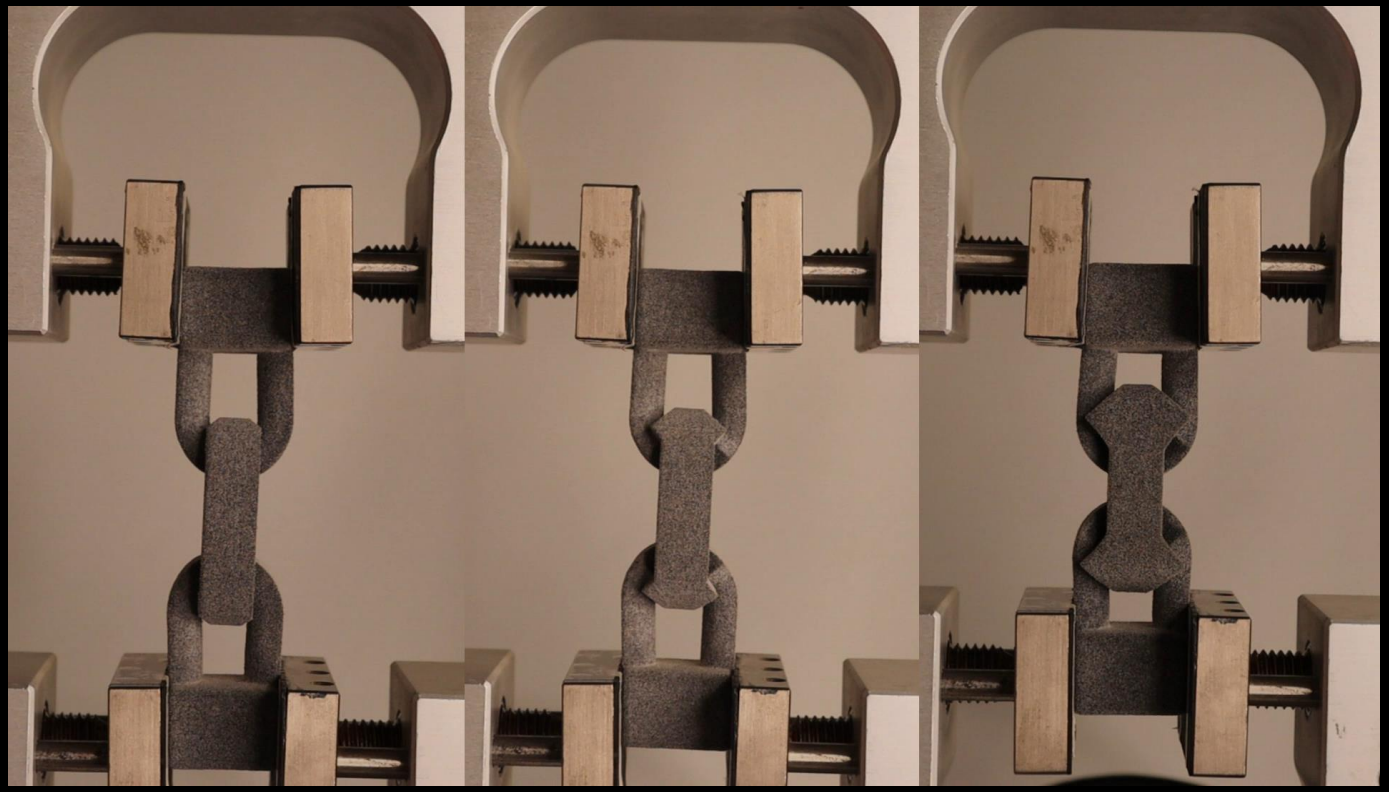

Quasi-Locking Chain: Rate = 150% Strain per Min
Strain
0.00
0.05
0.10
0.15
0.20
0.25
0.30
100
80
60
40
20
0
Force (N)
0
2
4
6
8
10
12
14
16
Digital Position (mm)
Light 2
Light

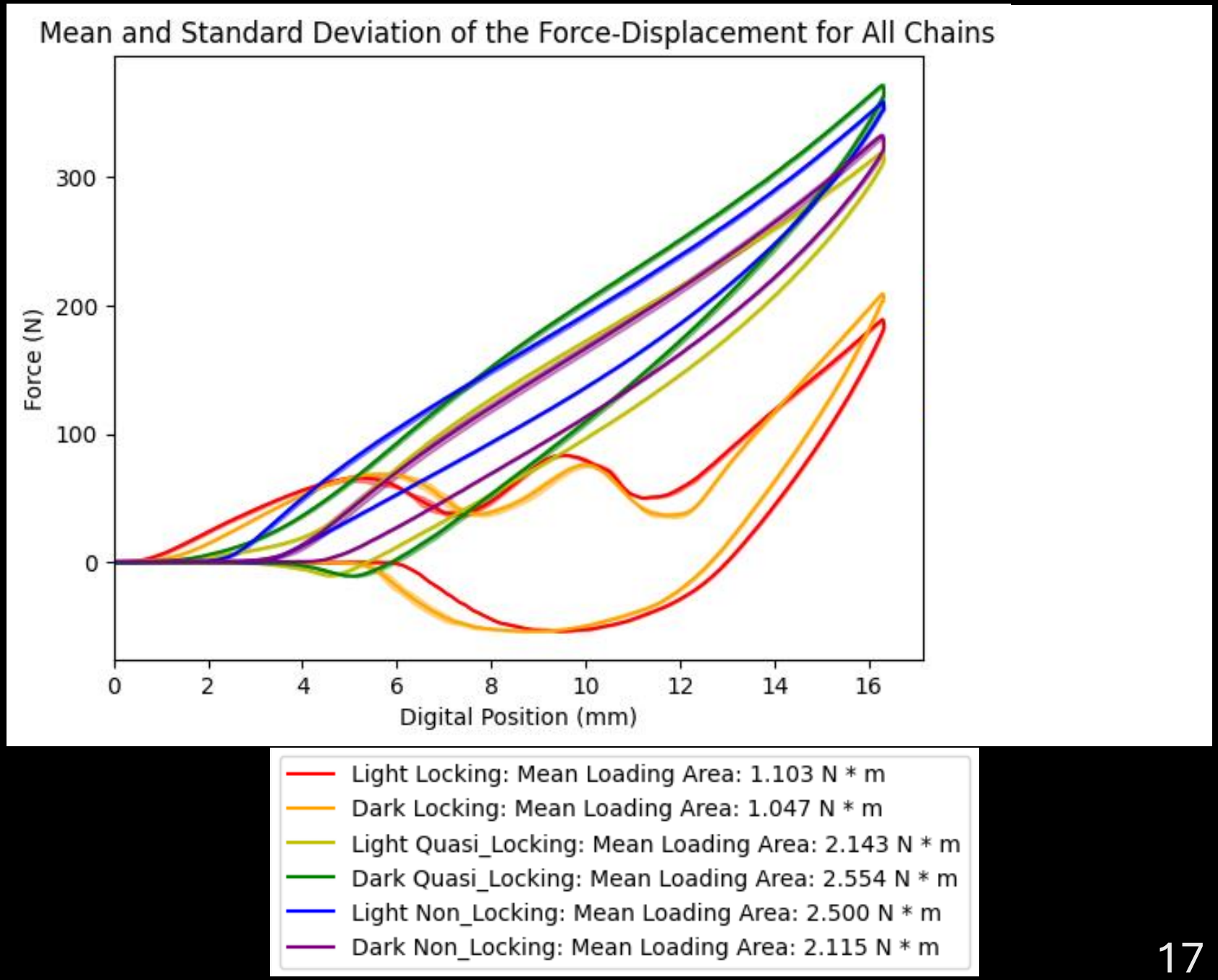
How to align everything?

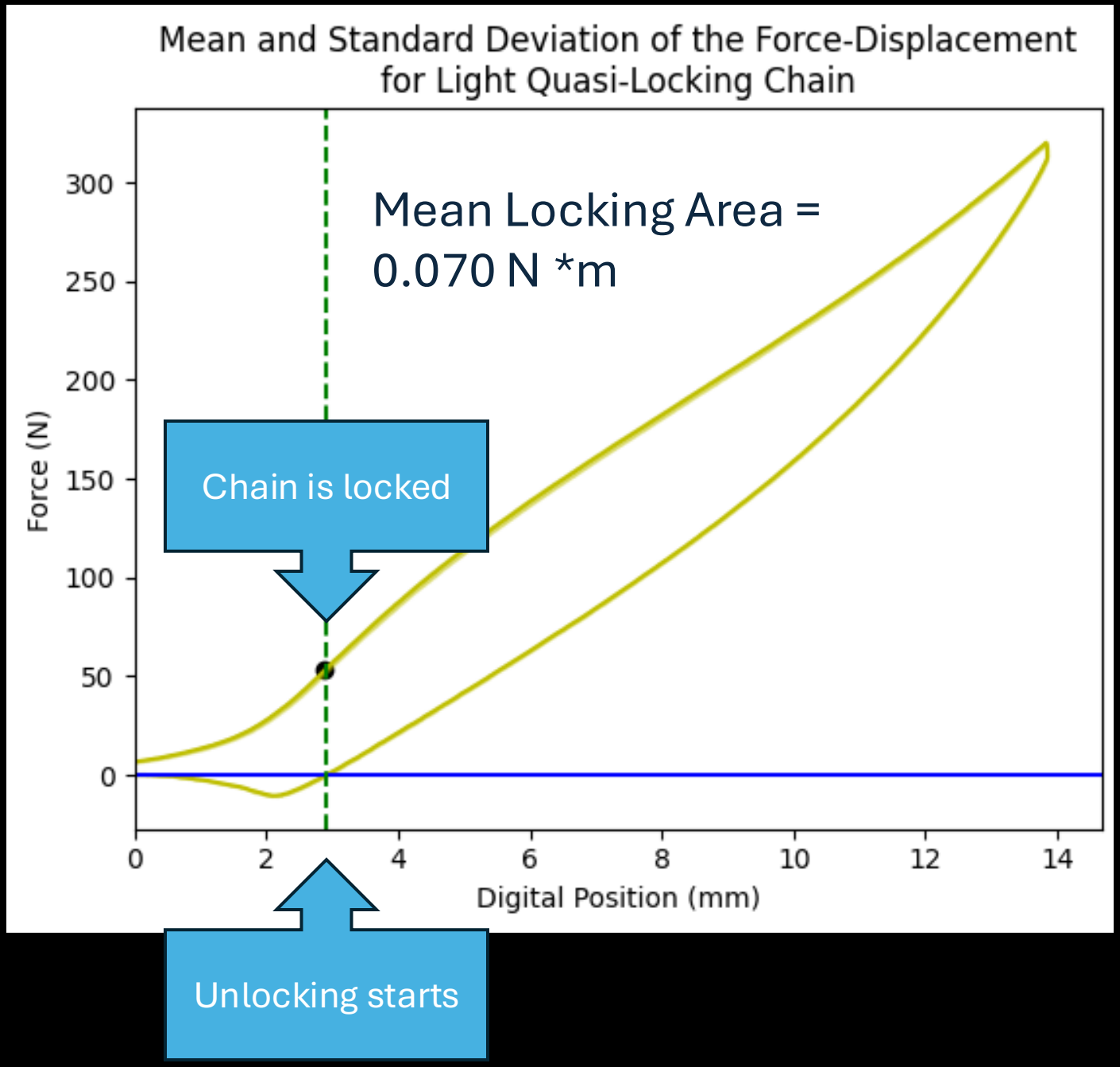


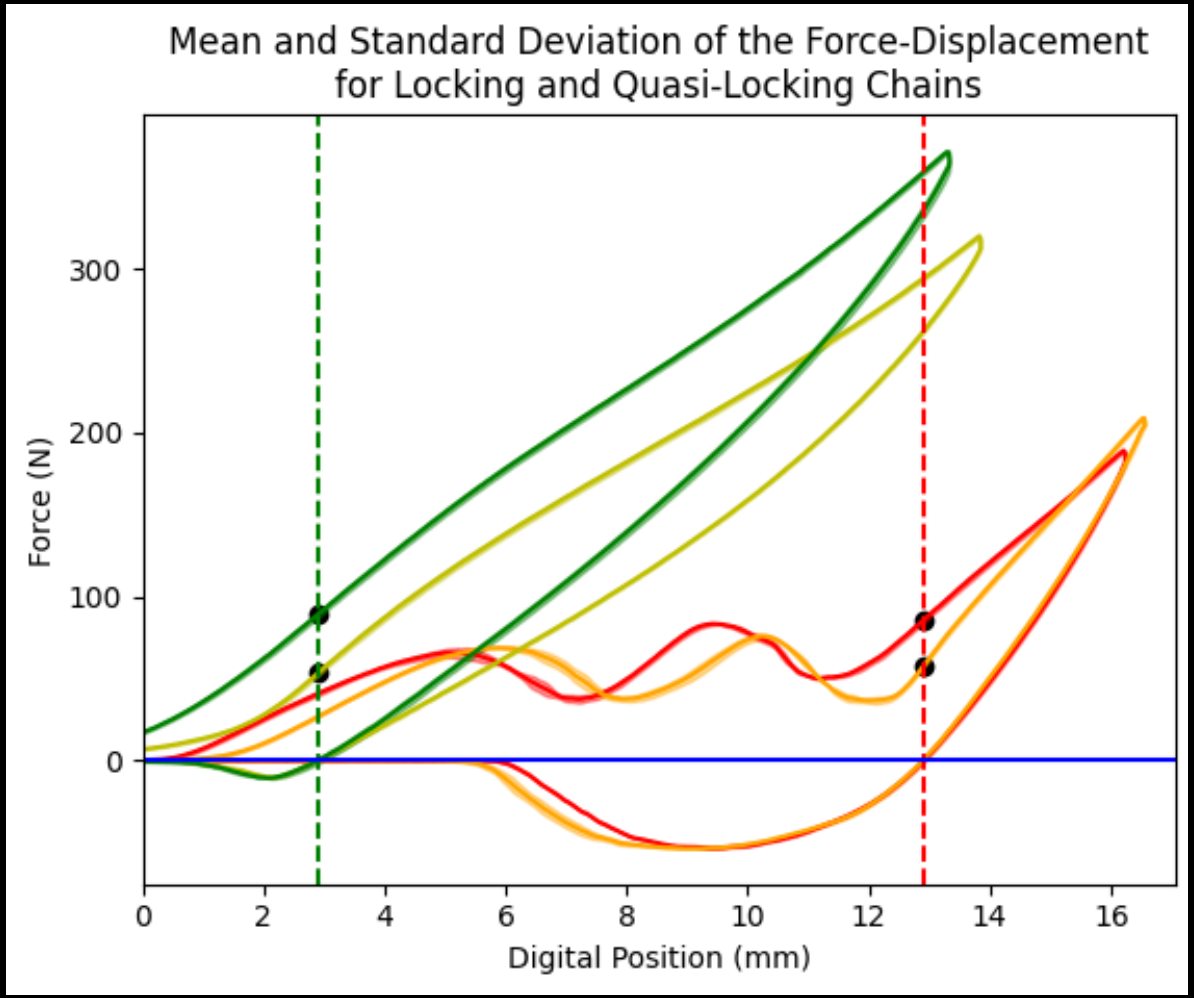
Light Locking Chain, Mean Loading Area: 0.80 N * m
Dark Locking Chain, Mean Loading Area: 0.79 N * m
Light Quasi-Locking Test1, Loading Area: 0.06 N * m
Dark Quasi-Locking Test1, Loading Area: 0.57 N * m
Light Non-Locking Test1, Loading Area: 0.02 N * m
Dark Non-Locking Test1, Loading Area: 0.18 N * m

Loading Rate = 150% Strain per Minute



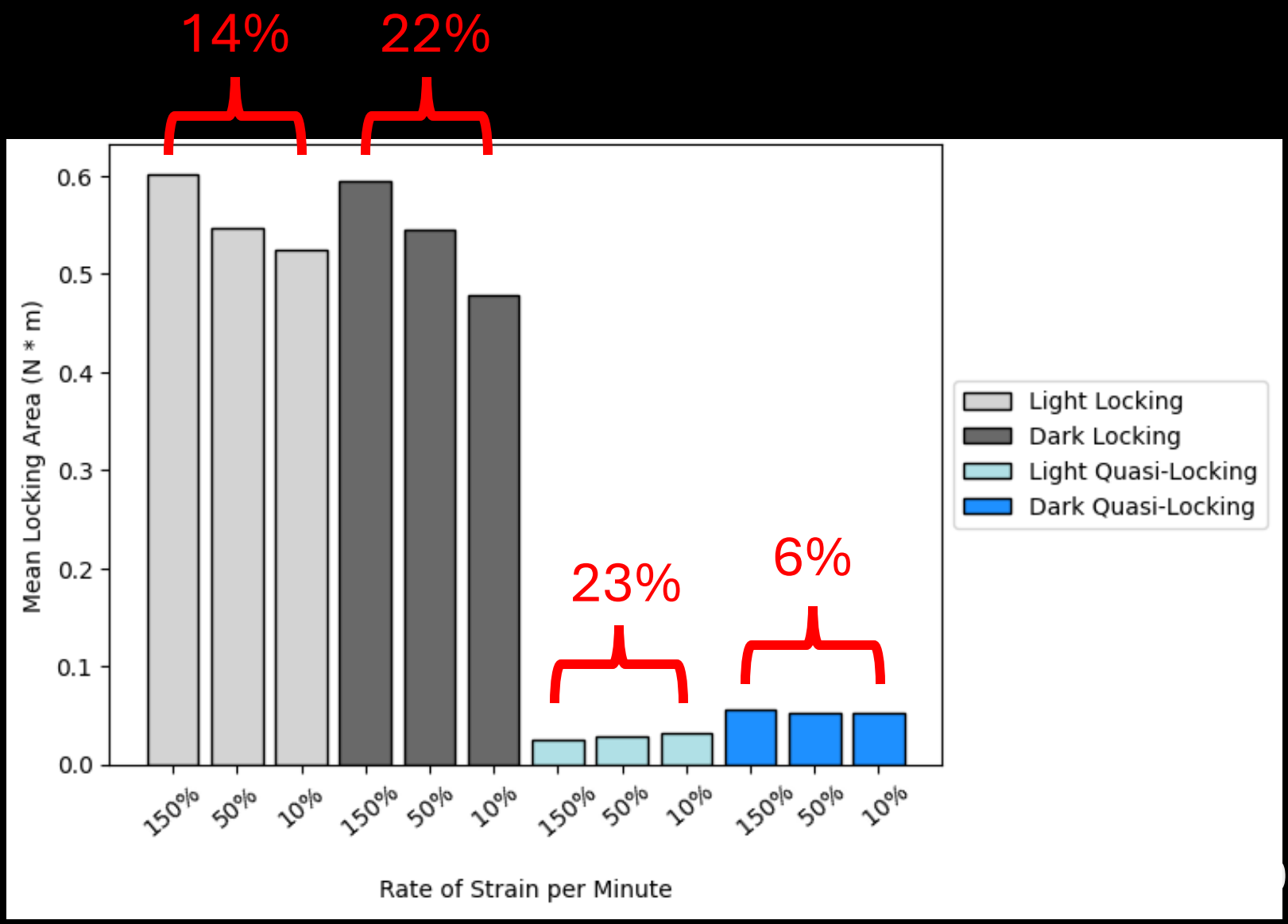

Mean and Standard Deviation of the Force-Displacement for All Chains
Force (N)
300
200
100
0
0
2
4
6
8
10
12
14
16
Digital Position (mm)
Light Locking: Mean Loading Area: 1.103 N * m
Dark Locking: Mean Loading Area: 1.047 N * m
Light Quasi_Locking: Mean Loading Area: 2.143 N * m
Dark Quasi_Locking: Mean Loading Area: 2.554 N * m
Light Non_Locking: Mean Loading Area: 2.500 N * m
Dark Non_Locking: Mean Loading Area: 2.115 N * m


Mean and Standard Deviation of the Force-Displacement for Light Quasi-Locking Chain
Mean Locking Area = 0.070 N *m
Chain is locked
Unlocking starts
Force (N)
Digital Position (mm)
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14

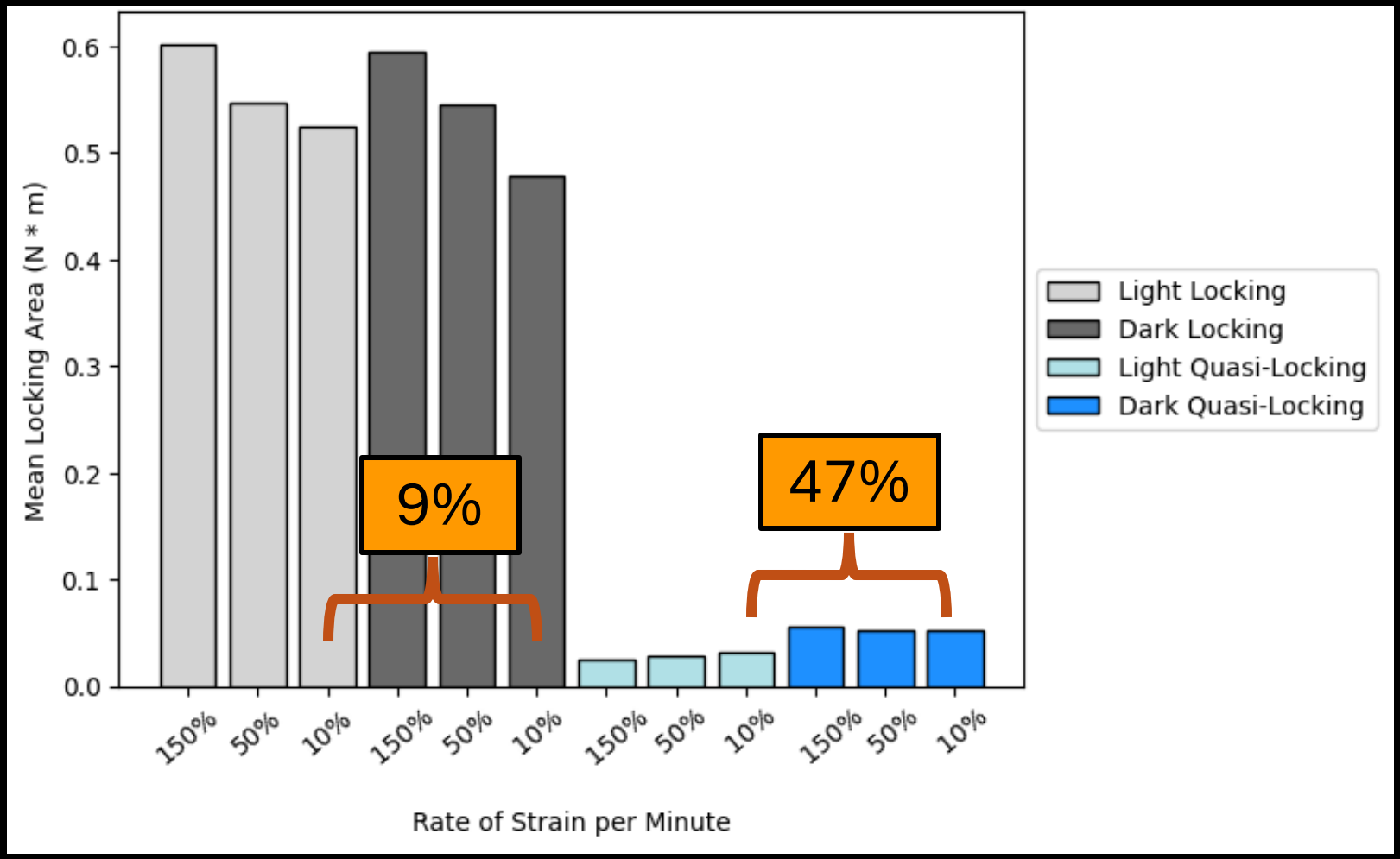


Light Locking: Mean Locking Area: 0.642 N * m
Dark Locking: Mean Locking Area: 0.551 N * m
Light Quasi_Locking: Mean Locking Area: 0.070 N * m
Dark Quasi_Locking: Mean Locking Area: 0.155 N * m
Locking Chain is locked
Quasi_Locking Chain is locked

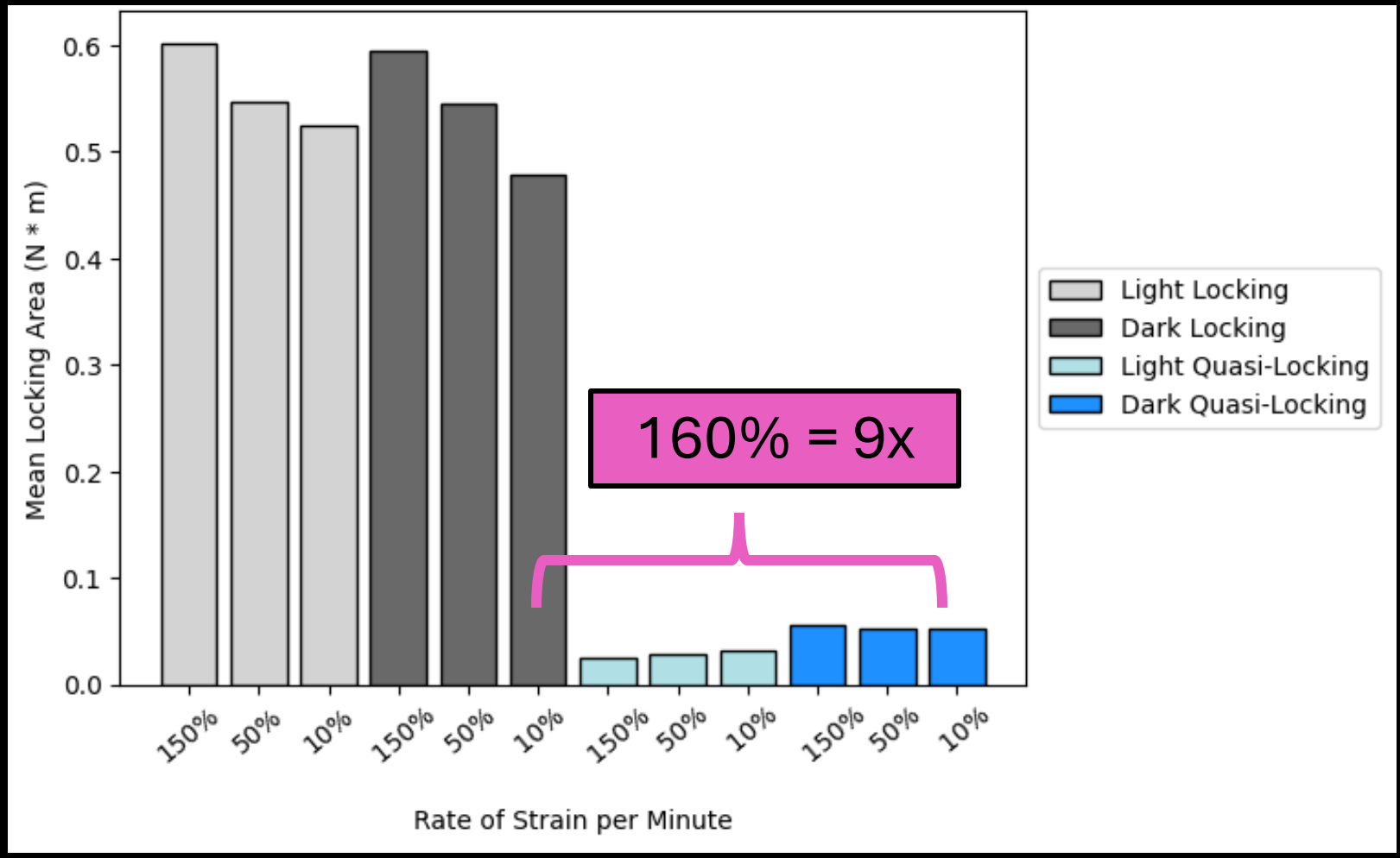
Effect of **Loading Rate** on Mean Locking Area of Locking and Quasi-Locking Chains



Effect of **Friction** on Mean Locking Area of Locking and Quasi-Locking Chains



Effect of **Geometry** on Mean Locking Area



References

- Slide 2: https://doi.org/10.48550/arXiv.2406.00316
- Slide 4:
  - https://www.freepik.com/free-vector/green-snake-cartoon-character-isolated-white-background_18179789.htm#query=cartoon%20snake&position=21&from_view=keyword&track=ais_hybrid&uuid=0b601619-1ec1-43bf-b66b-87856c7dc74e
  - https://www.waterlinesquare.com/far-fetched-new-york/

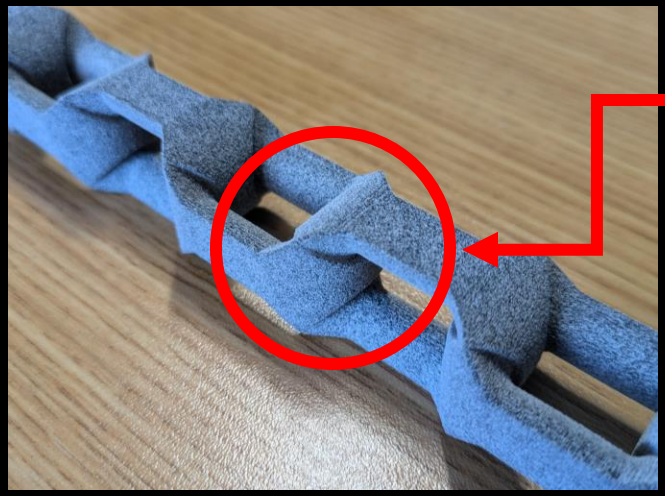
Jabri’s turn

11-Particle Chains

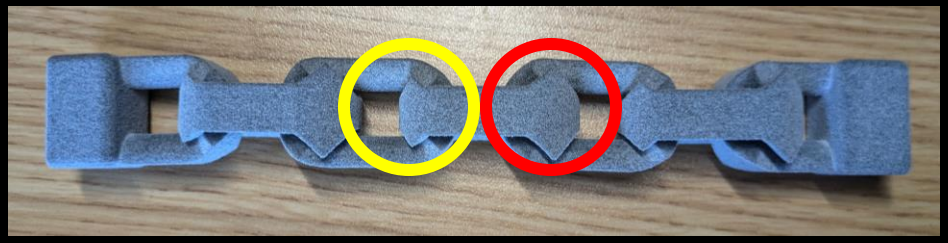
11-Particle Locking Chain:

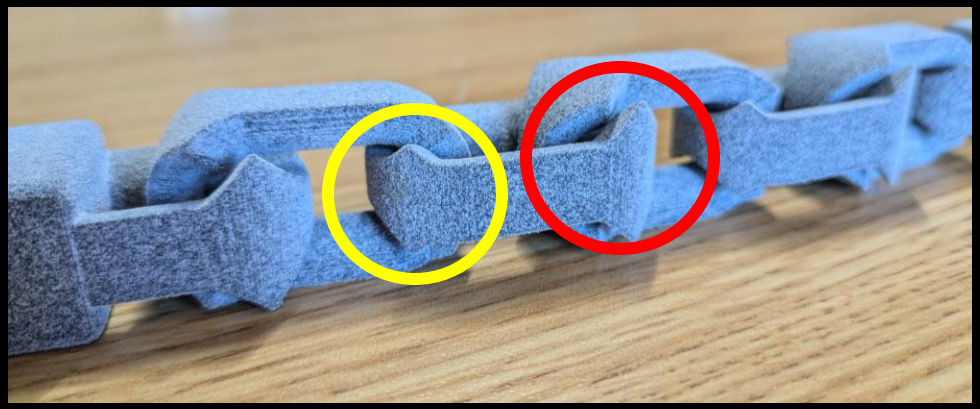
11-Particle Quasi-Locking Chain:

Fused 11-Particle Chain



Mixed 7-Particle Chain

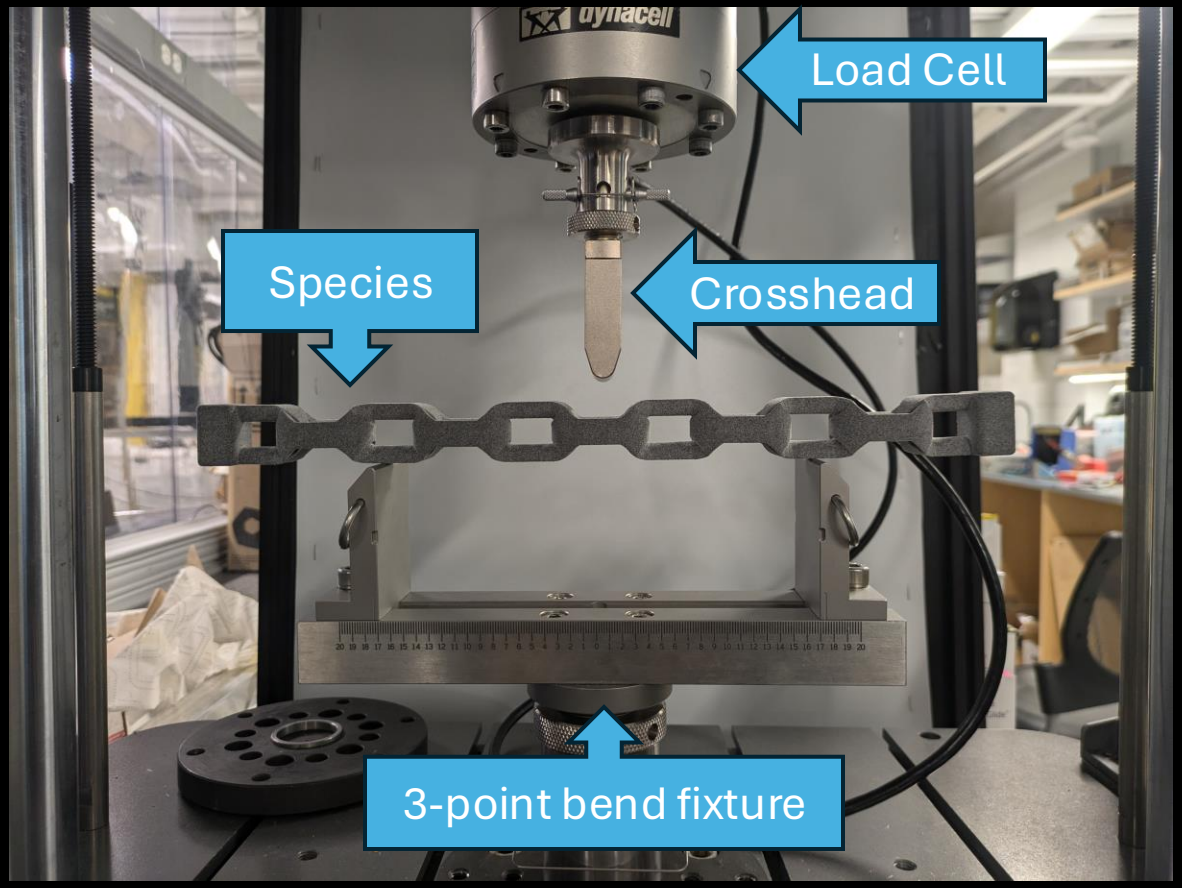




Yellow: Quasi-Locking joint

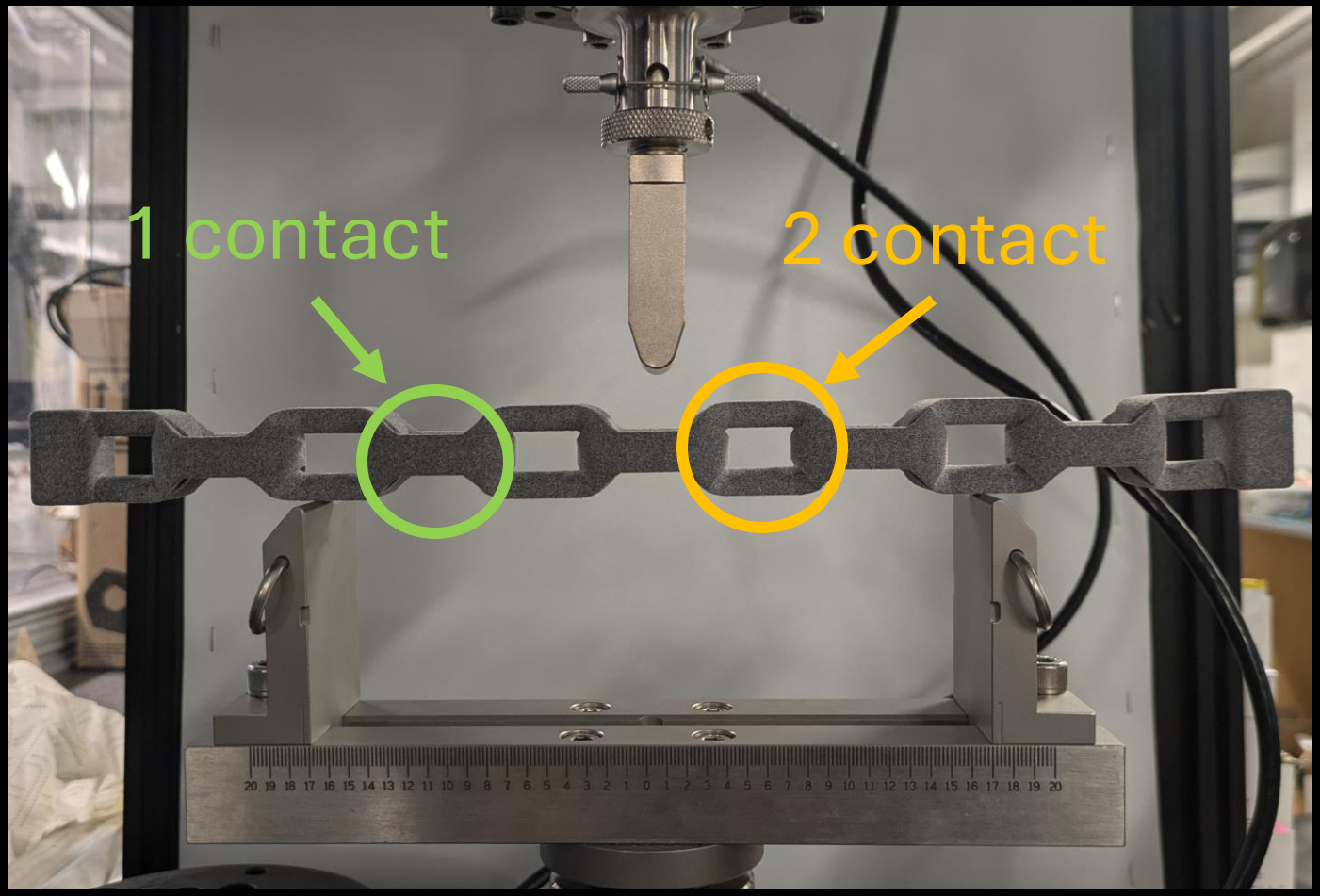
Red: Locking Joint

Setup for 3-Point Bend Test



Followed ASTM D790 standard test methods

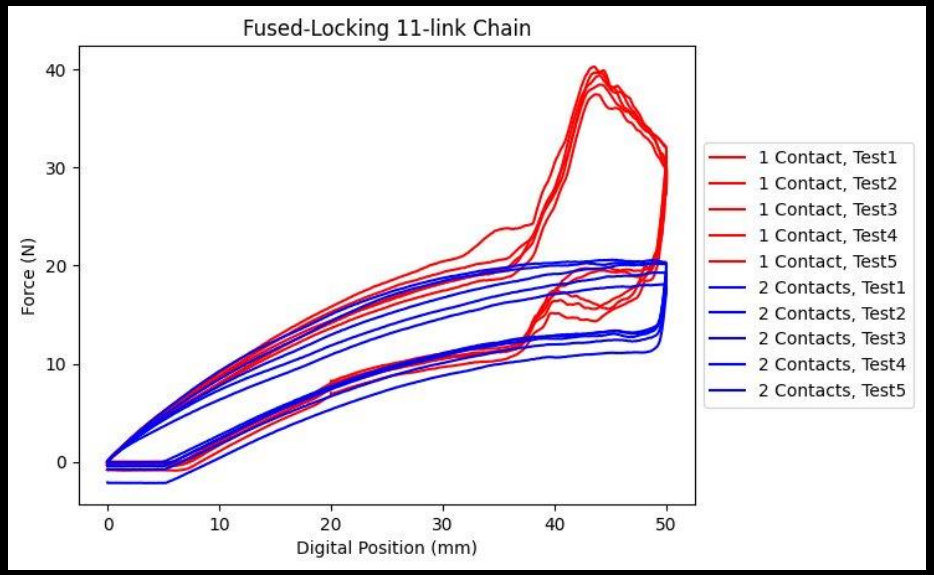
Species Orientation for 3-Point Bend Tests

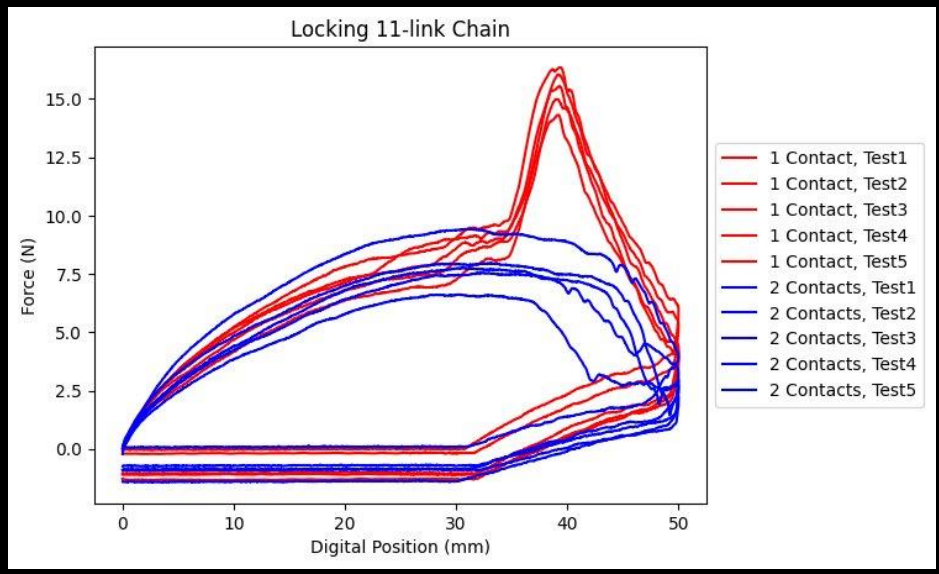


Three-Point Bending Tests for 11-Particle Chains

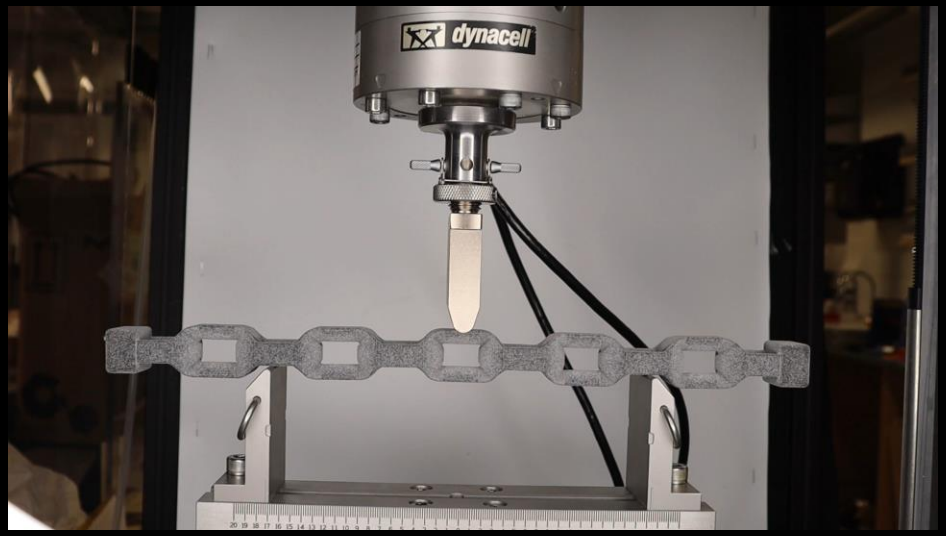
- Does a locking chain in its locked state behave similarly to it's rigid/fused counterpart?
- Will the orientation of a chain affect its performace?

Three-Point Bending Tests for 11-Particle Chains Results





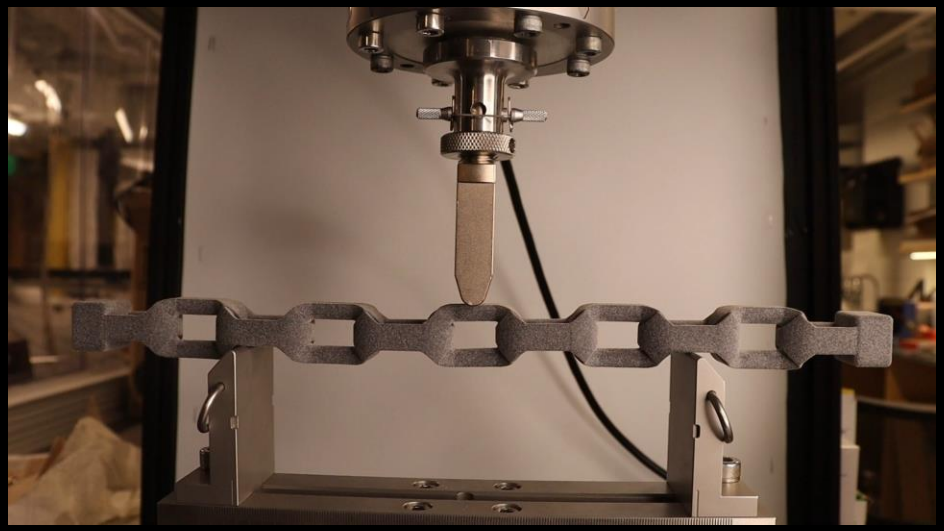
Fused 11-Particle Chains



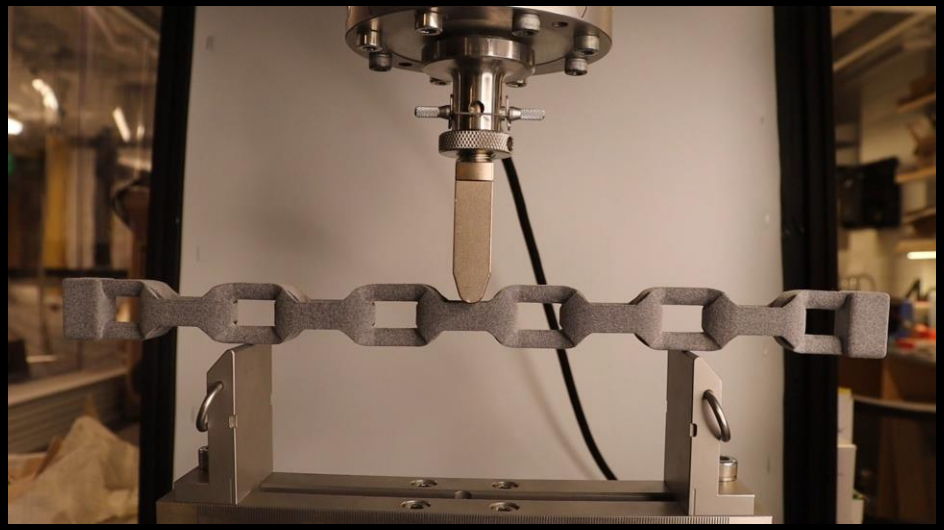
1 Contact

2 Contact

Locking 11-Particle Chains

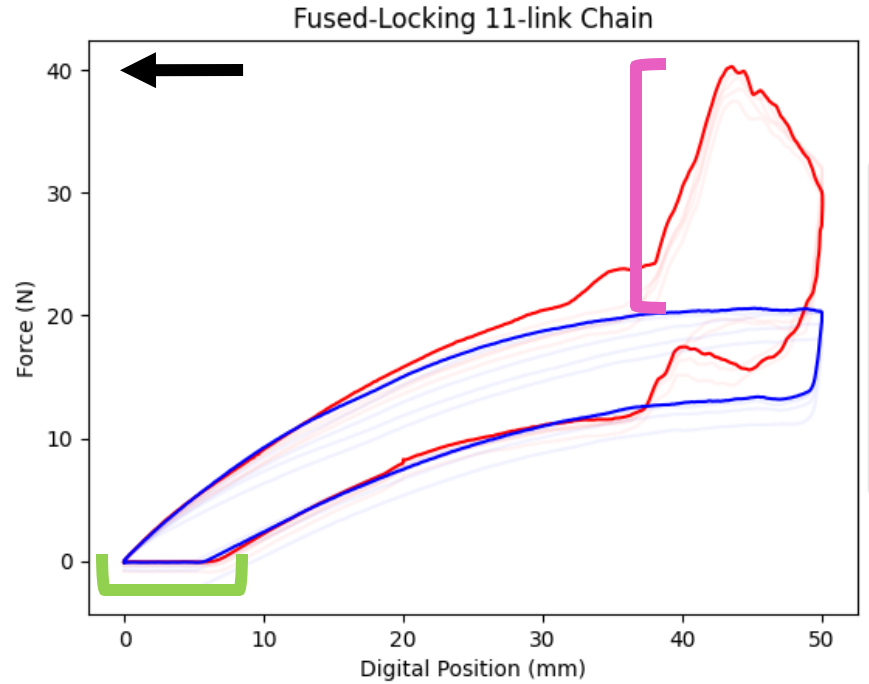


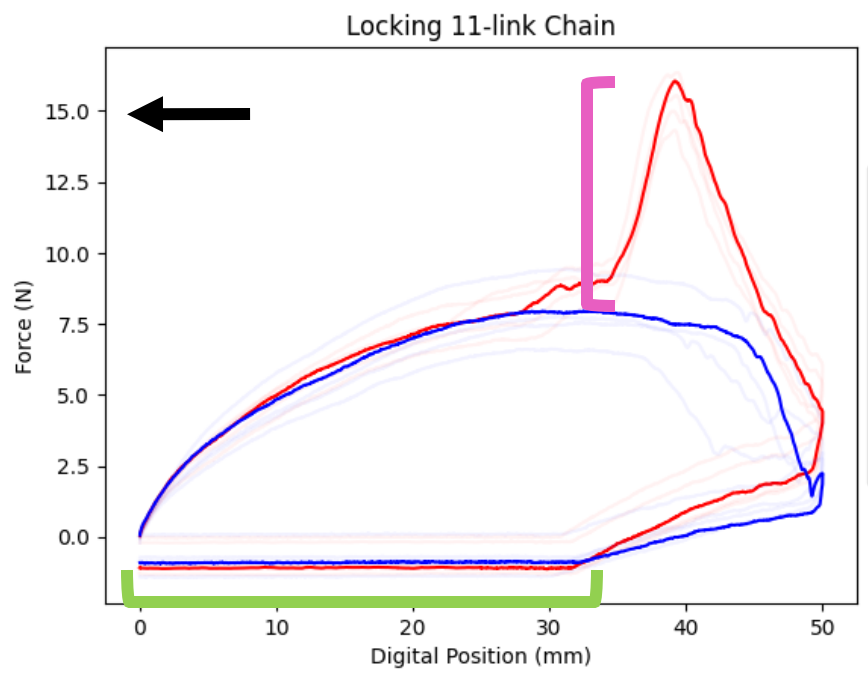
1 Contact



2 Contact

Three-Point Bending Tests for 11-Particle Chains



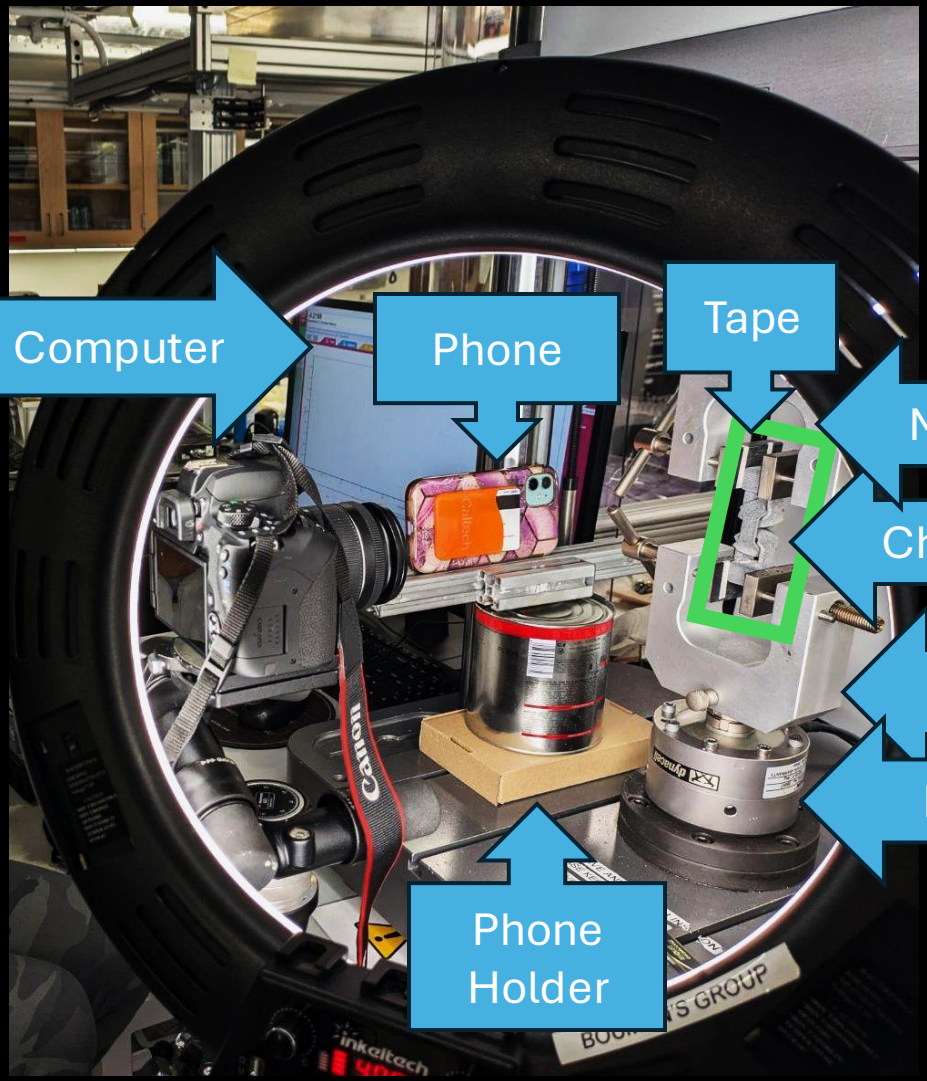


	Fused, 1 Contact	Fused, 2 Contact	Locking, 1 Contact	Locking, 2 Contact
Avg. Bending Modulus	1.13	1.05	0.943	0.982

Three-Point Bending Tests for 11-Particle Chains

- Chain orientation doesn't affect performance.
- When locking chain is in its locked state it behaves similarly to a rigid body

Setup for Longer Tensile Tests



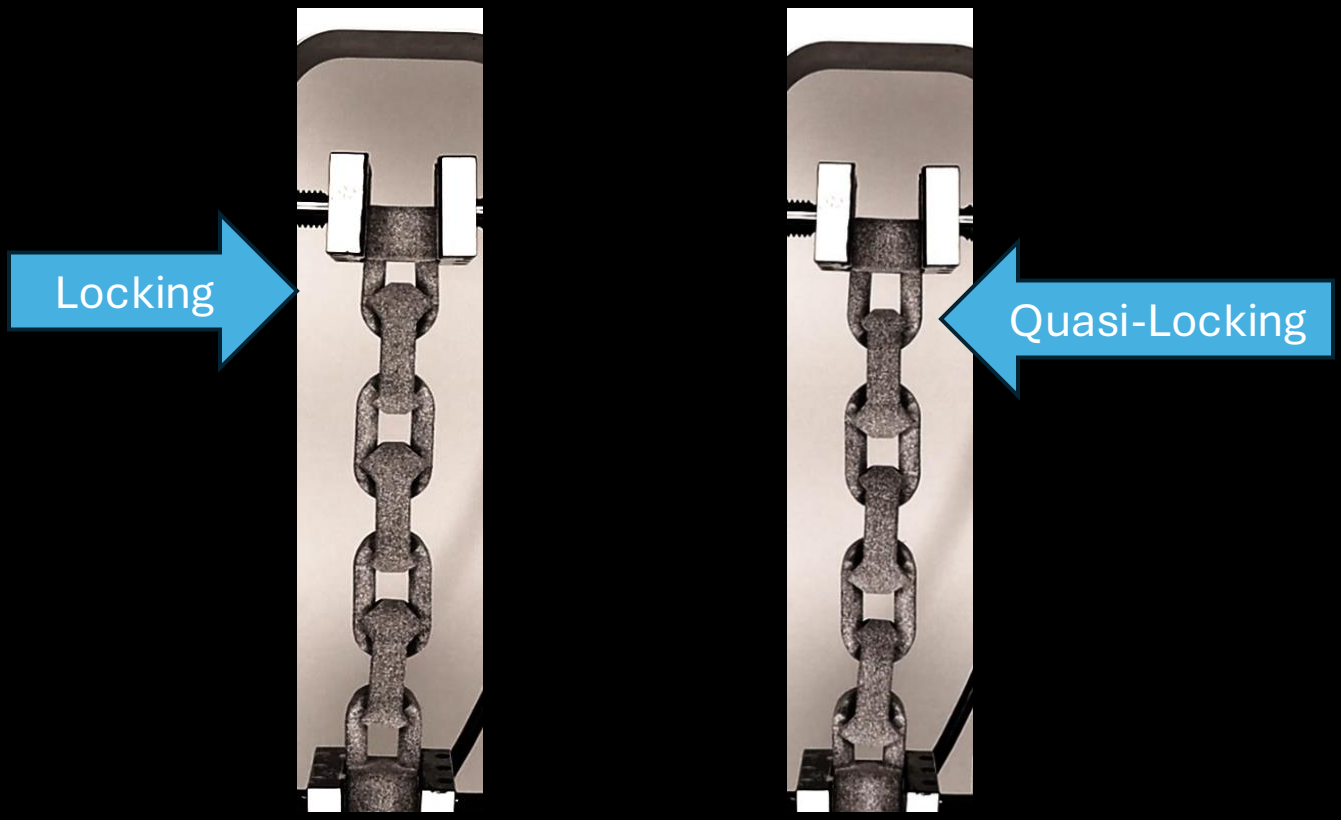
- Similar setup
- Applied many of the lessons learned

Tensile Tests

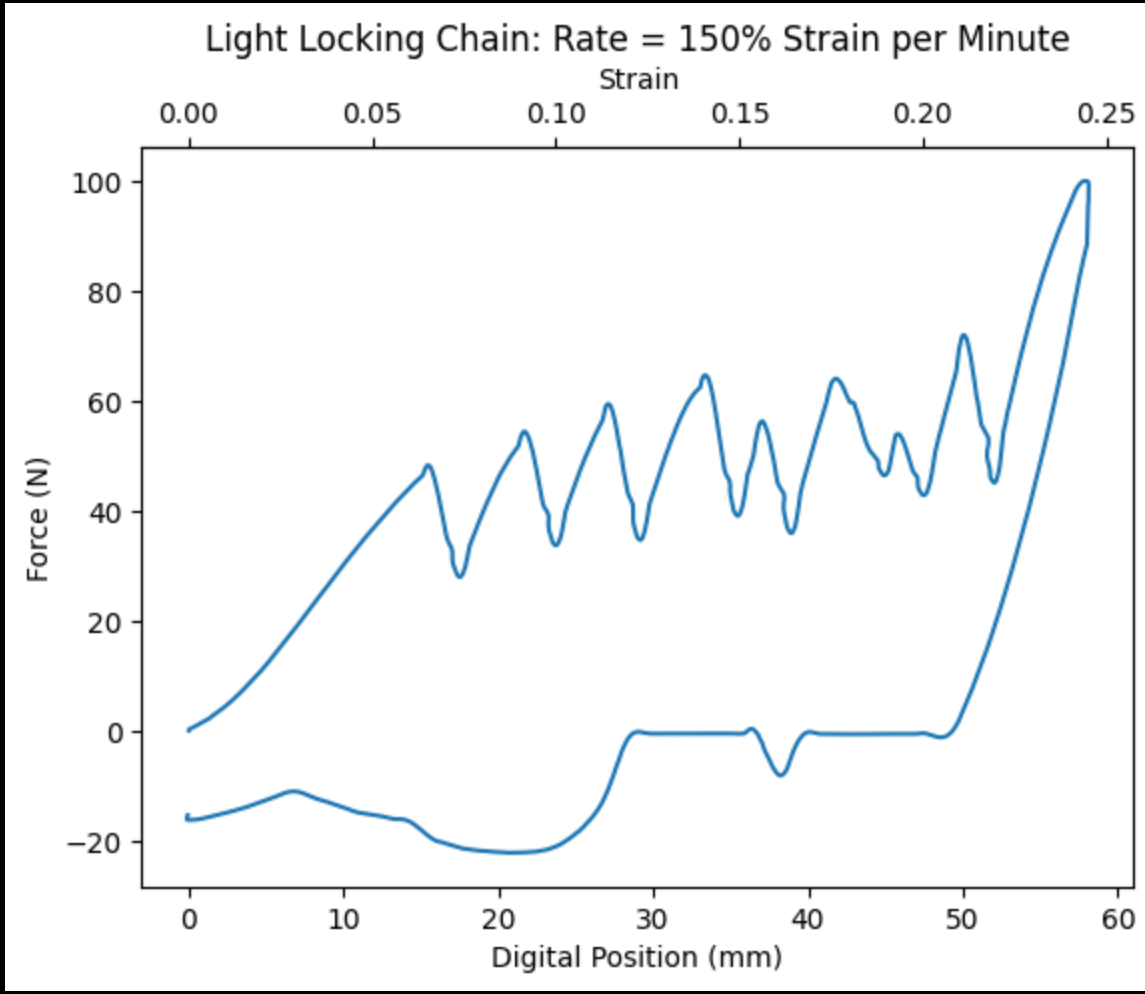
Tensile Tests were performed on:

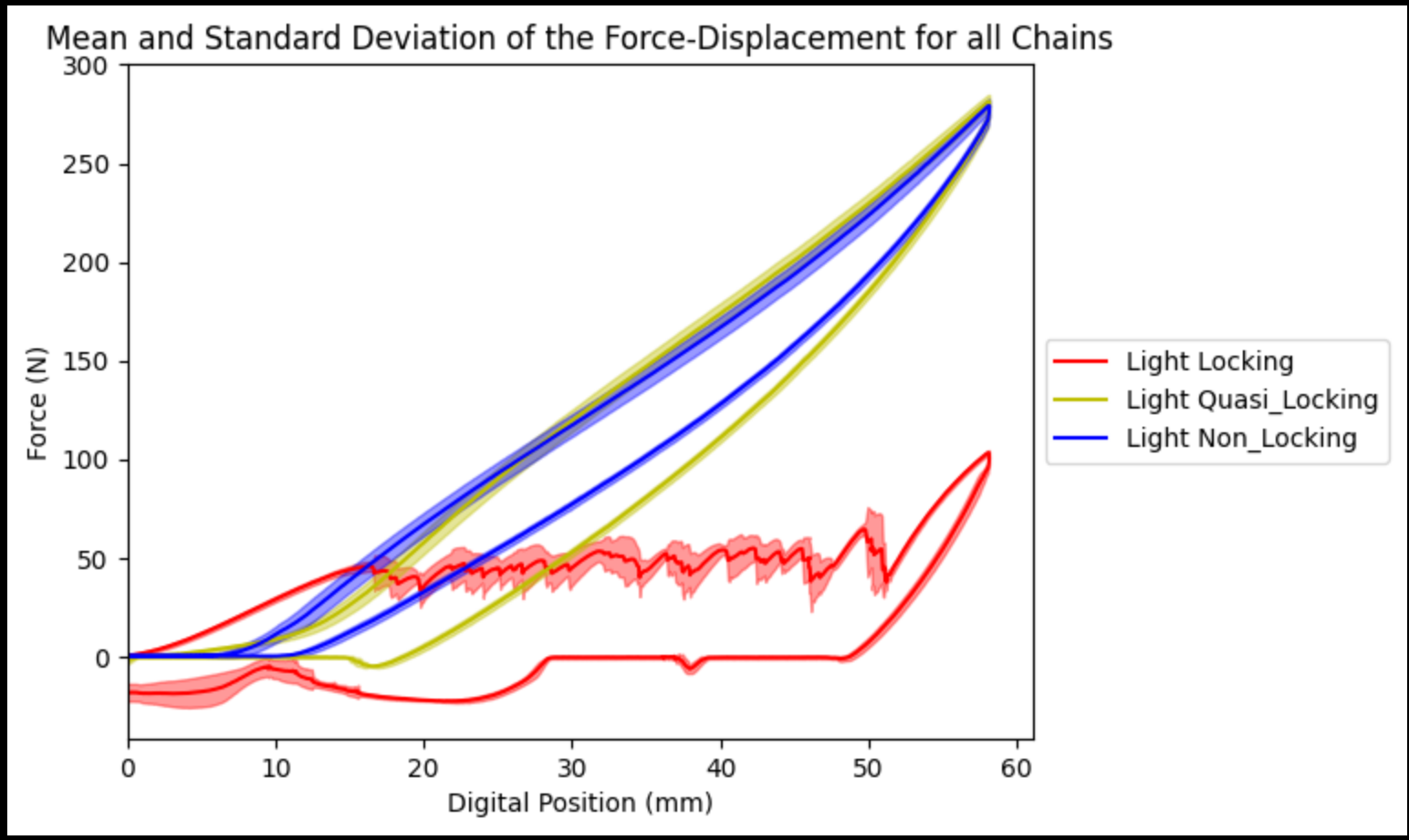
- 11-Particle Locking Chain
- 11-Particle Quasi-Locking Chain
- 11-Particle Non-Locking Chain
- Mixed 7-Particle Chains
  - MixedL
  - MixedQ

Mixed 7-Particle Chains

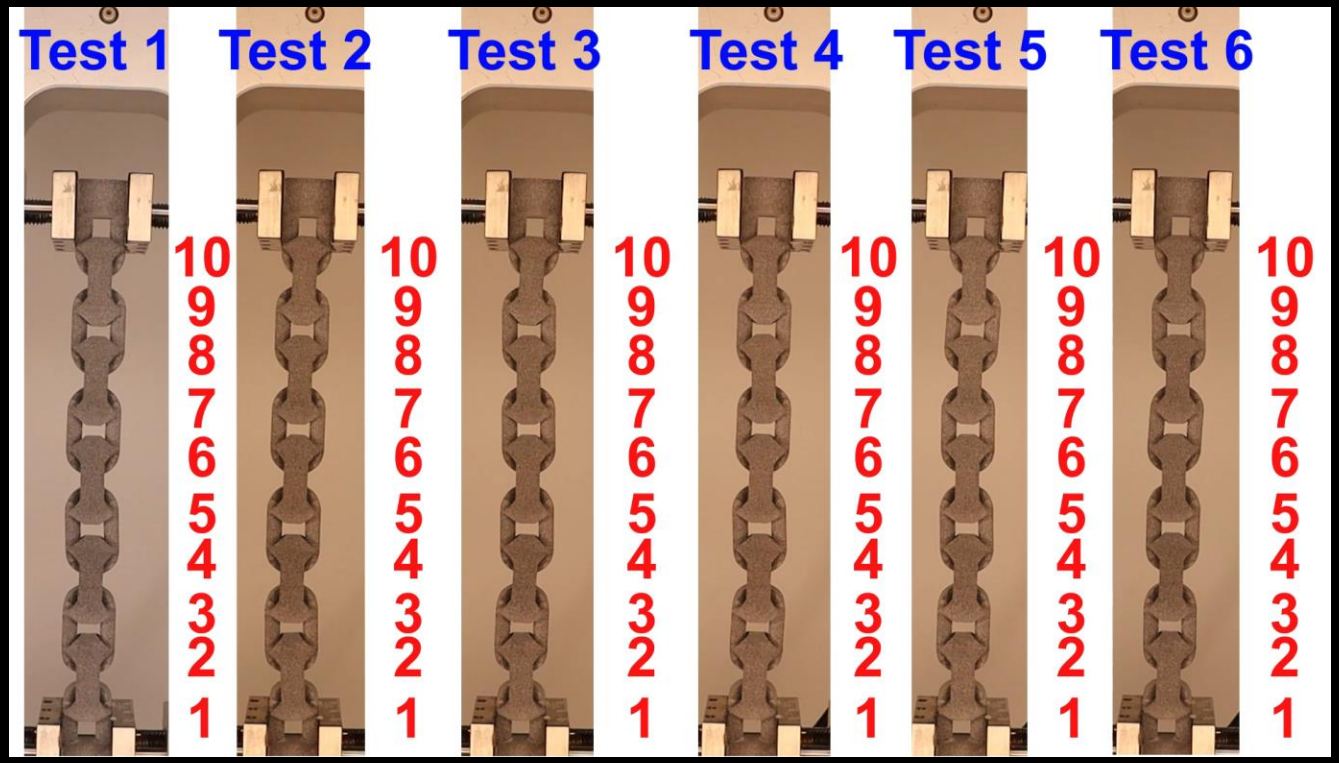


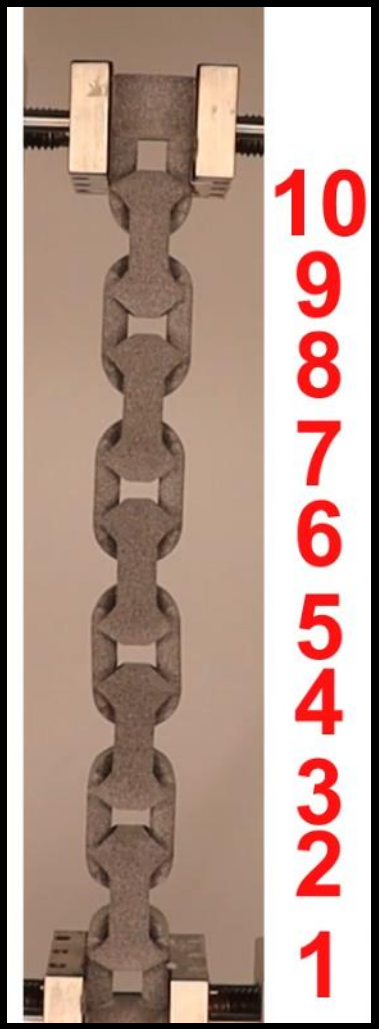
MixedL MixedQ


Light Locking Chain: Rate = 150% Strain per Minute
Strain
0.00
0.05
0.10
0.15
0.20
0.25
100
80
60
40
20
0
−20
Force (N)
0
10
20
30
40
50
60
Digital Position (mm)


Mean and Standard Deviation of the Force-Displacement for all Chains
Force (N)
Digital Position (mm)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
Light Locking
Light Quasi_Locking
Light Non_Locking

11-Particle Locking Chain





Snapability

Test1: **4**5236789

Test2: **4**5236789

Test3: **4**5279863

Test4: 56**4**23789

Test5: **4**5278639

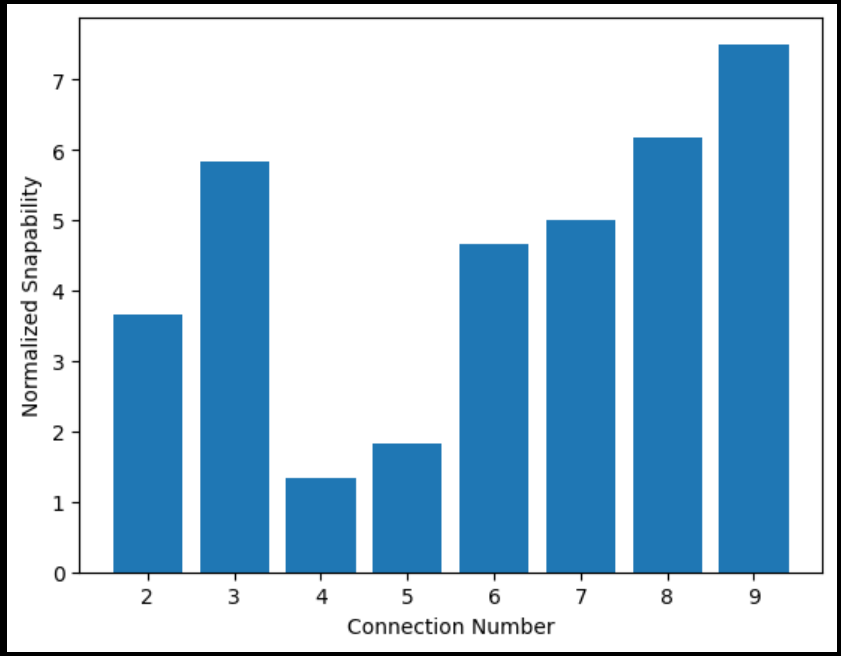
Test6: **4**5678239

Normalized Snapability

= (Order of Snapping) * (Number of Occurences) / (Number of Tests)

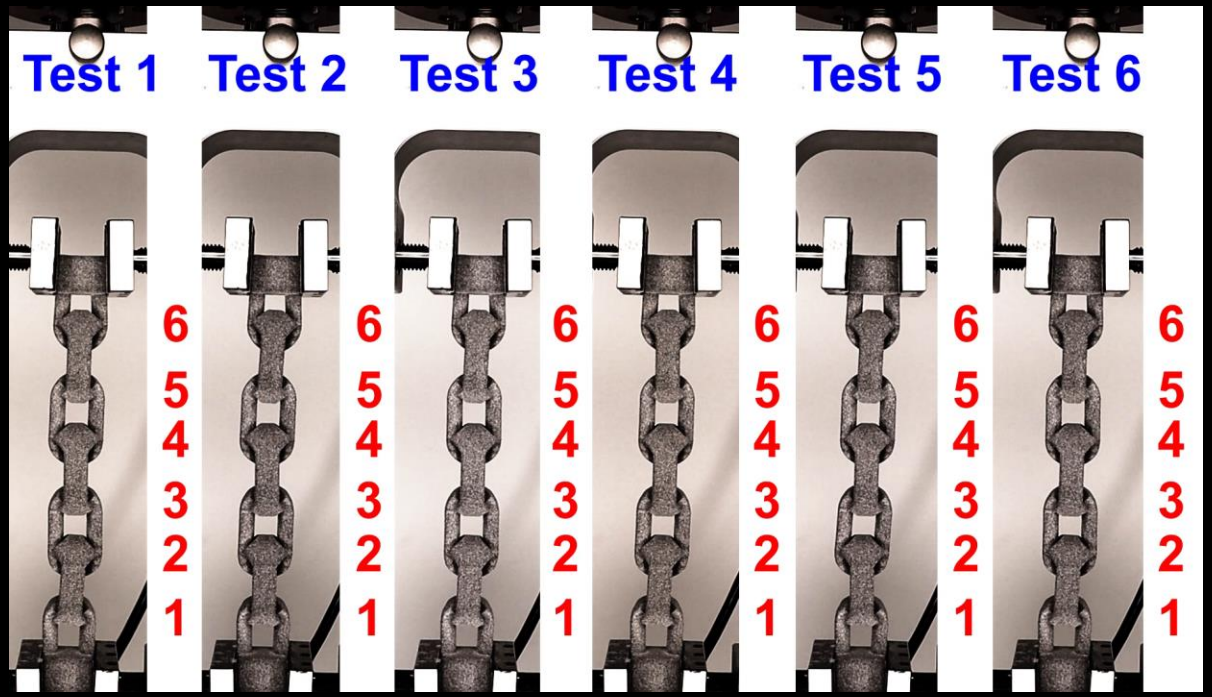
Normalized Snapability for Connection 4

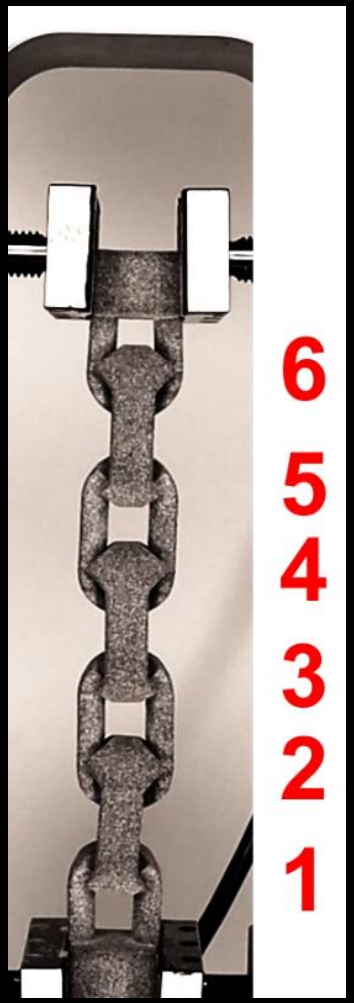
= (1 * 5 + 3 * 1) / 6 = 4/3



MixedL-Locking Chain

Mixed**L** = Locking mechanism on top





Snapability for MixedL-Locking Chain

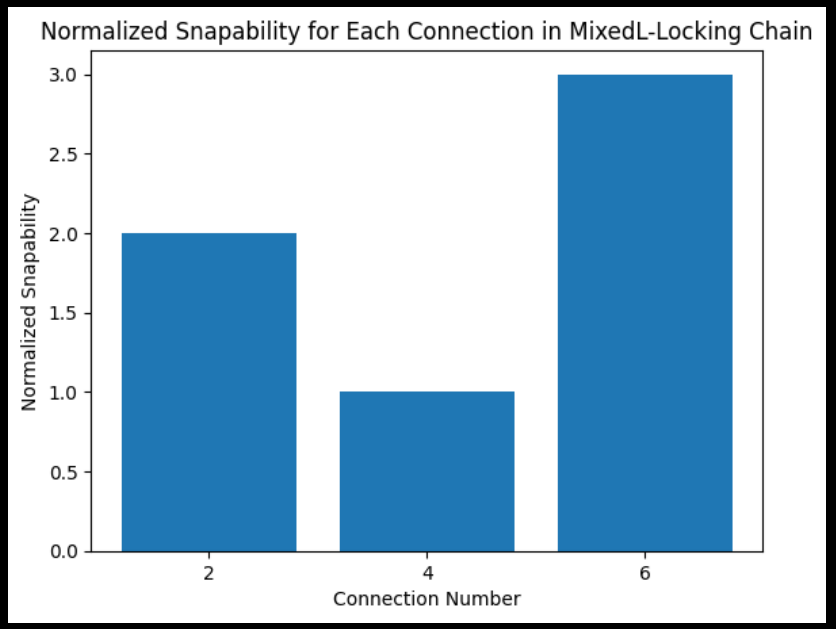
For all six tests: **4**26

Normalized Snapability

= (Order of Snapping) * (Number of Occurences) / (Number of Tests)

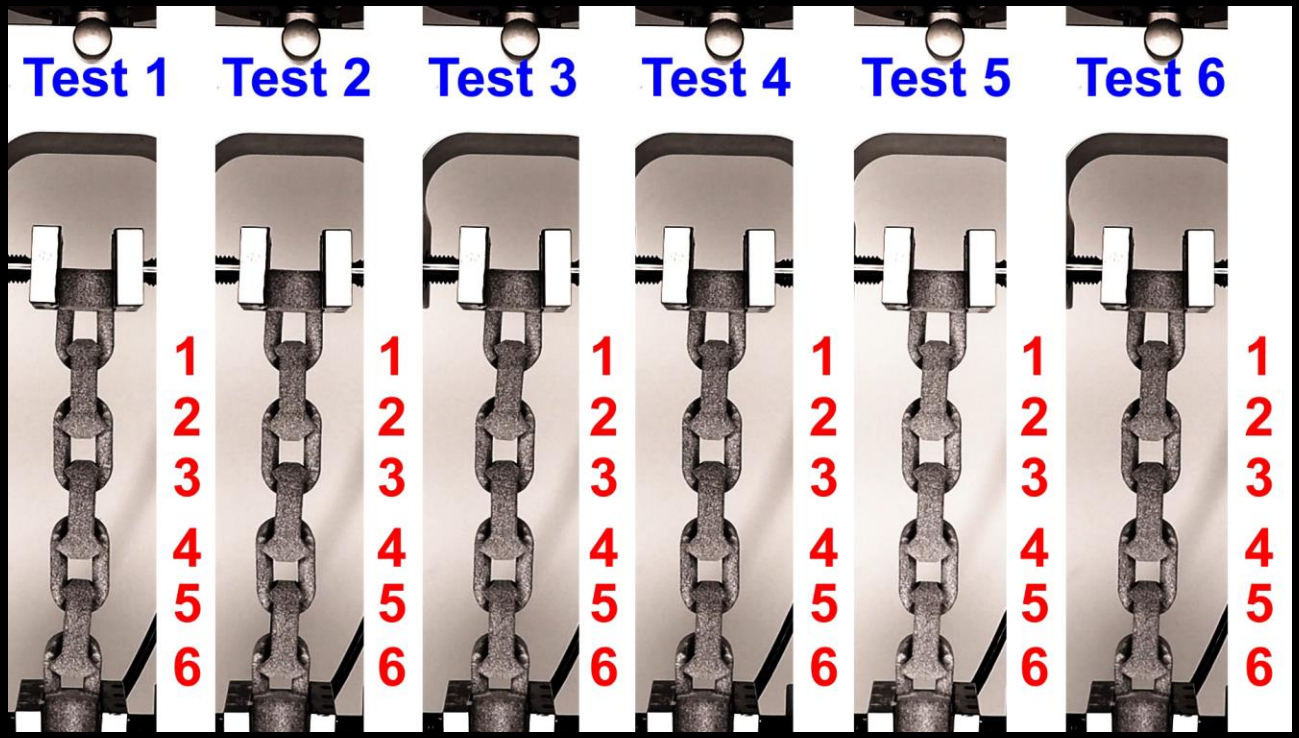
Normalized Snapability for Connection 4

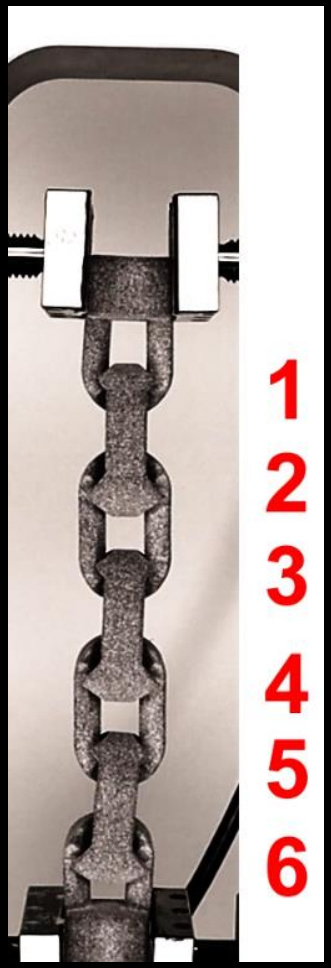
= (1 * 6) / 6 = 1



MixedQ-Locking Chain

Mixed**Q** = Quasi-Locking mechanism on top





Snapability for MixedQ-Locking Chain

Test1: **4**26

Test2: **4**26

Test3: 2**4**6

Test4: 2**4**6

Test5: **4**26

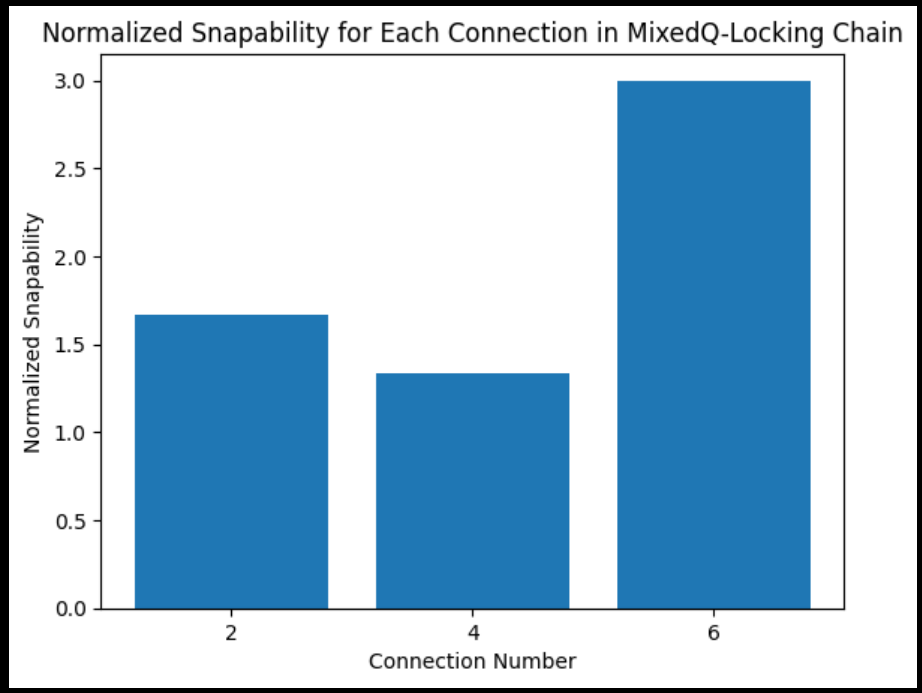
Test6: **4**26

Normalized Snapability

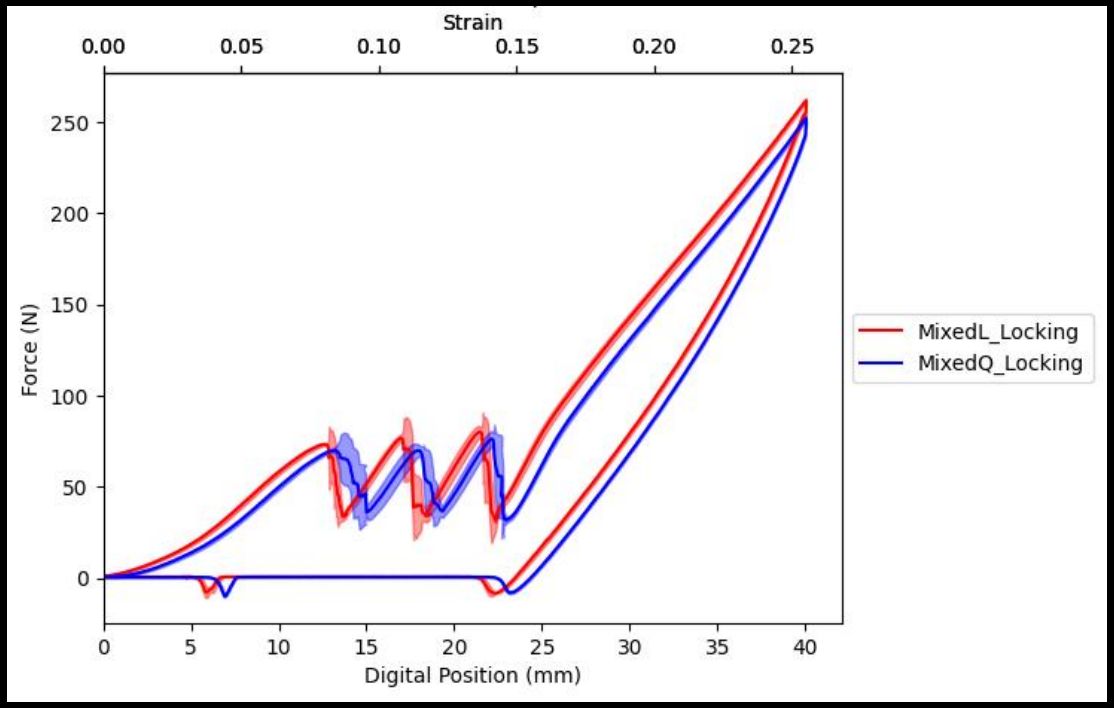
= (Order of Snapping) * (Number of Occurences) / (Number of Tests)

Normalized Snapability for Connection 4

= (1 * 4 + 2 * 2) / 6 = 4/3



Tensile Tests for MixedL-Locking and MixedQ-Locking Chain



Future Works

- Compression tests on fused 11-particle chain and compare against 11-particle locking chain in locked state
- Use VIC

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