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Aponeurosis Inspired Variable Stiffness for Soft Robotics

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INTRODUCTION

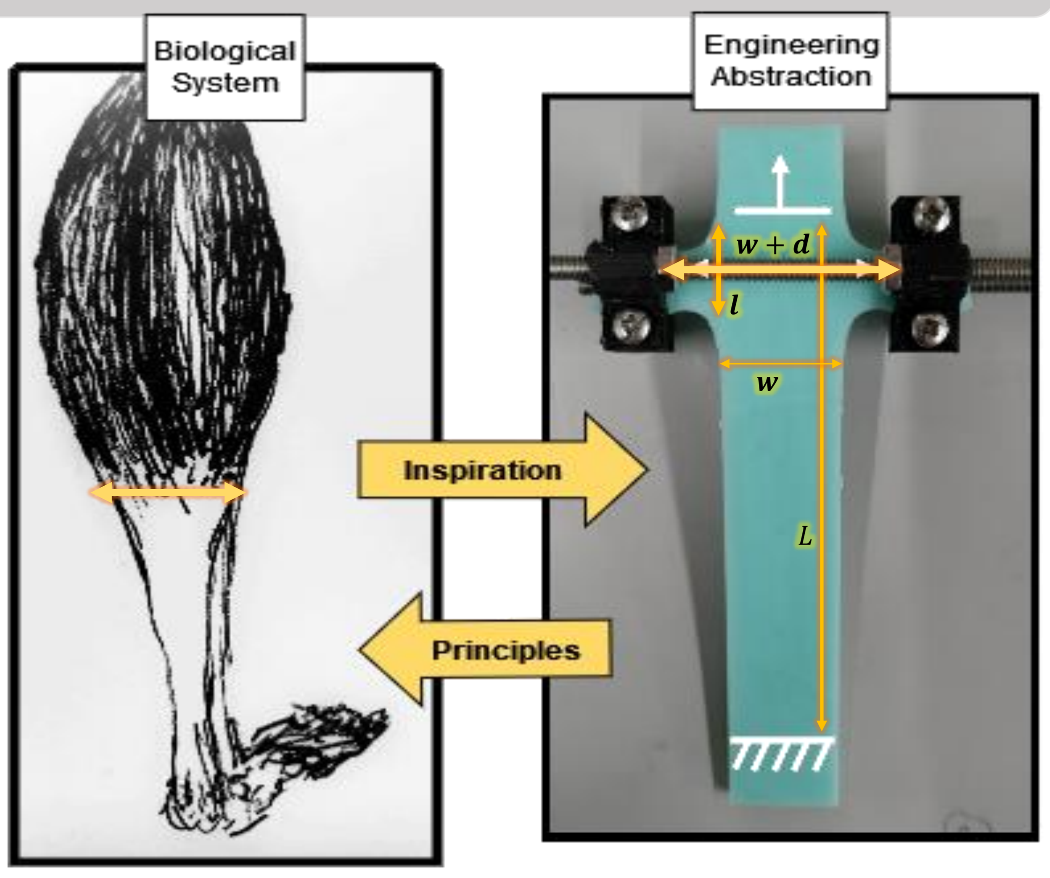


Figure 0 (Above): *Biomechanics and Robotics are potentially synergistic research disciplines. Figure shows cartoon of aponeurosis on biological system vs engineering abstraction. Geometry used in this work is defined .*

- **Soft Robotics** is closing the gap between the two by using compliant materials and new technologies [1,4] and may provide avenues to explore biomechanical principles in relatively simpler engineering systems.
- **Biology**: Lateral deformation of the aponeurosis during muscular contraction has been shown to affect the stiffness response of the aponeurosis and possibly connected tendons, imbuing them with *variable stiffness* (VS)[2,3].
- **Robotics**: VS is a desired actuation feature allowing transient and controllable dynamics responses [5].
- Robotic VS mechanisms, while efficacious, can be complex and heavy, with large form factors [6,7].

Can a biologically inspired approach inform relatively minimalist VS mechanisms in robotic locomotion and provide insight into the biomechanical principle?

AIM / OBJECTIVES

- Use silicone elements to mimic tendon/aponeurosis and provide static lateral displacement to mimic transverse loading.
- Investigate the impact of varying lateral displacement and the length of the region laterally loaded on the force-displacement response of the element under tensile loads.

METHOD

Silicone elements of shore hardness 40 (*Smooth-On Mold Max 40*) are molded with geometry: 100mm x 20mm x 4mm (Figure 0). L is the length of the tendon. Each element has tabs on either side of its width of length, l, that can be clamped and displaced using a continuous stretching mechanism. Lateral displacement, d, is varied from 0 – 15mm (5mm increments) and load applied in longitudinal direction with a mechanical testing machine (Instron 3344) to 75% strain, measuring longitudinal force production, F_{lo}. *Digital Image Correlation* (DIC) was used to capture Von Mises strain in an isolated "aponeurosis" region.

RESULTS

- We hypothesized that an element would follow the biological literature's observations of increasing overall F_{lo} production (indicative of stiffness increases) with increasing d.
- Our data suggests an inversion to this hypothesis (Fig.1, Table.1).
- The reference stiffness is increased with a larger l and the effect of lateral displacement is also enhanced.
- Planar DIC studies of aponeurosis region show complex non-monotonic strain development (Fig 2).

l/L	$F_{max}(d = 0mm)$	$F_{max}(d = 15mm)$
40%	**60.5464 N**	**55.8956 N**
30%	**57.9772 N**	**48.7578 N**
20%	**48.2521 N**	**45.2853 N**
10%	**48.8686 N**	**47.3551 N**

Table 1 (Above): *Variations in maximum force production (at 75% longitudinal strain) for tested l/L ratios at the two extremes of lateral displacement.*

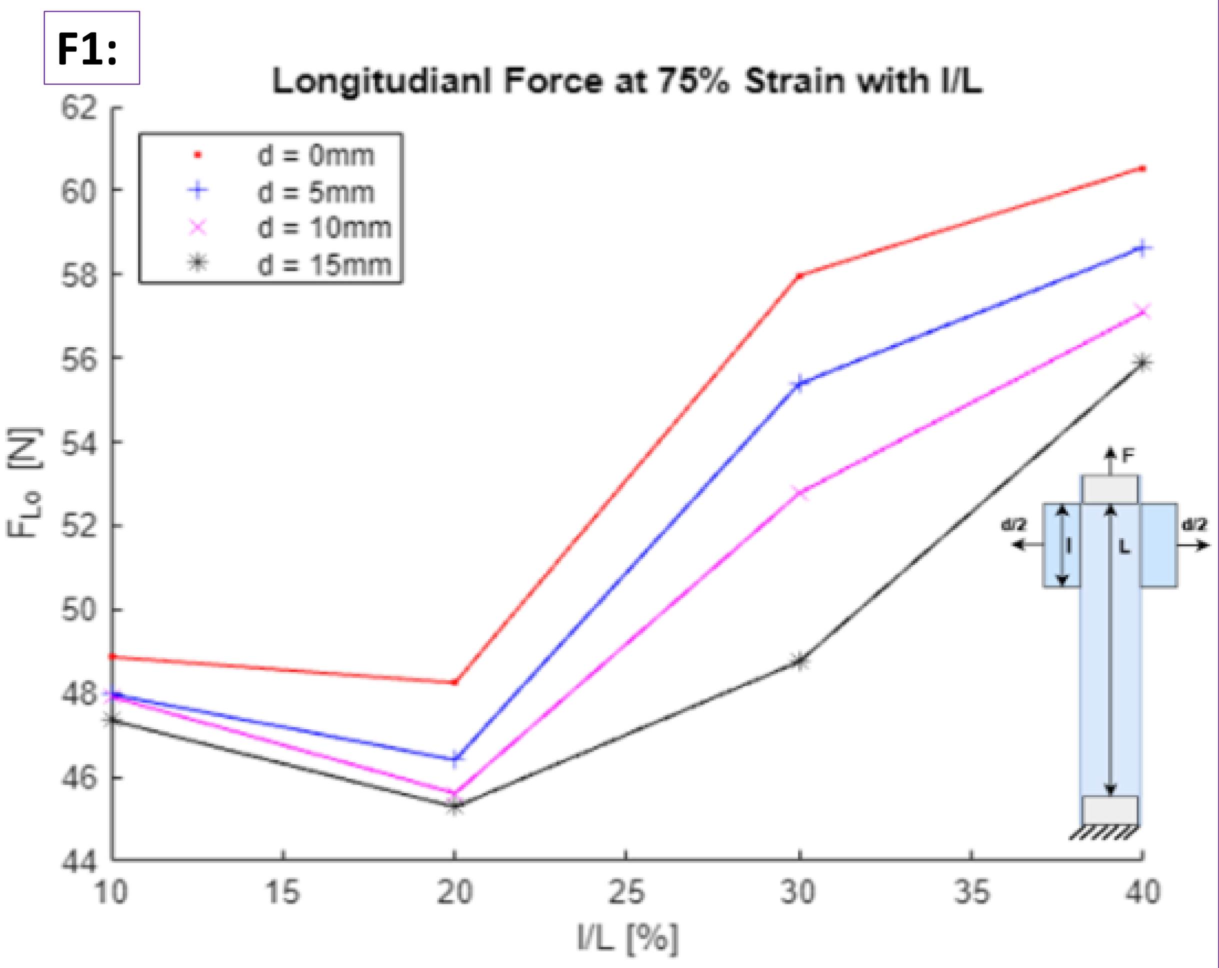
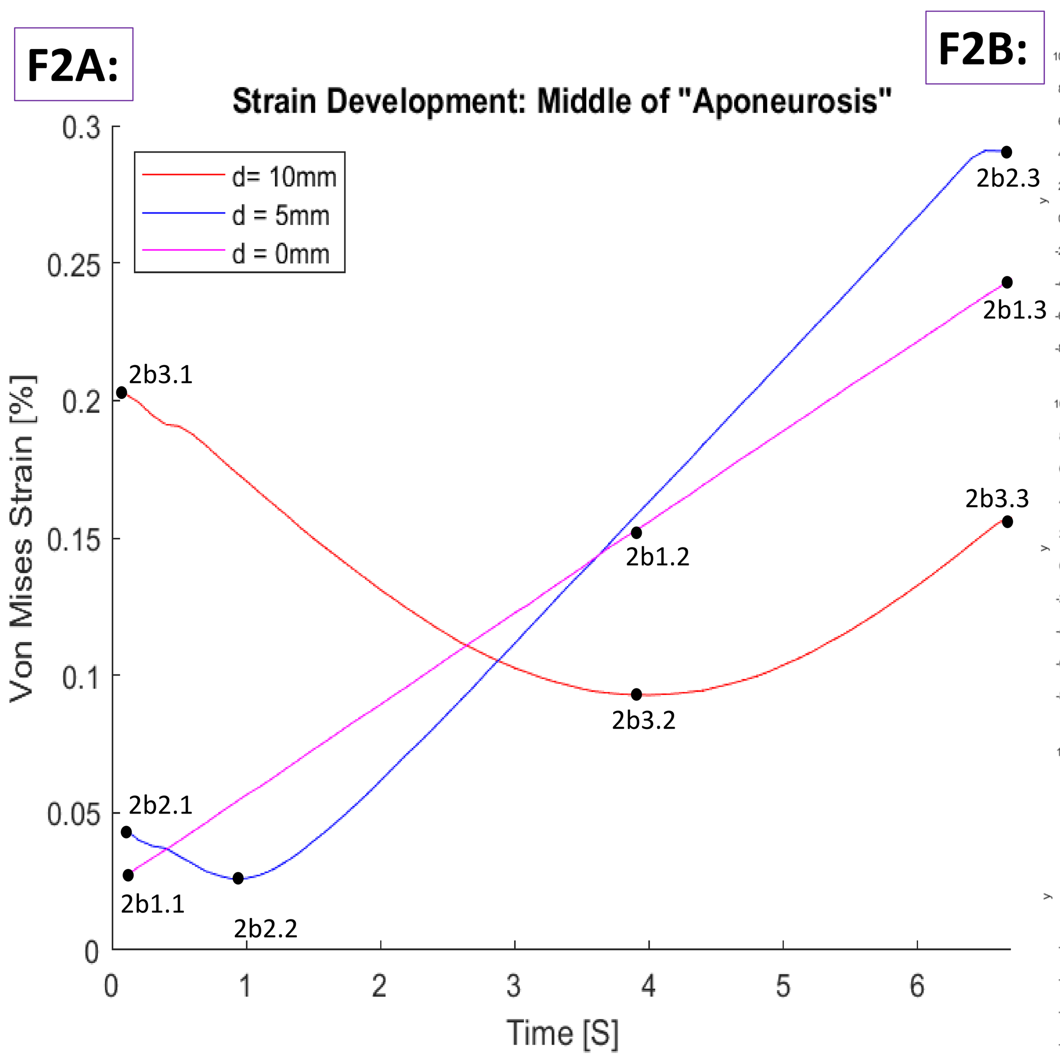
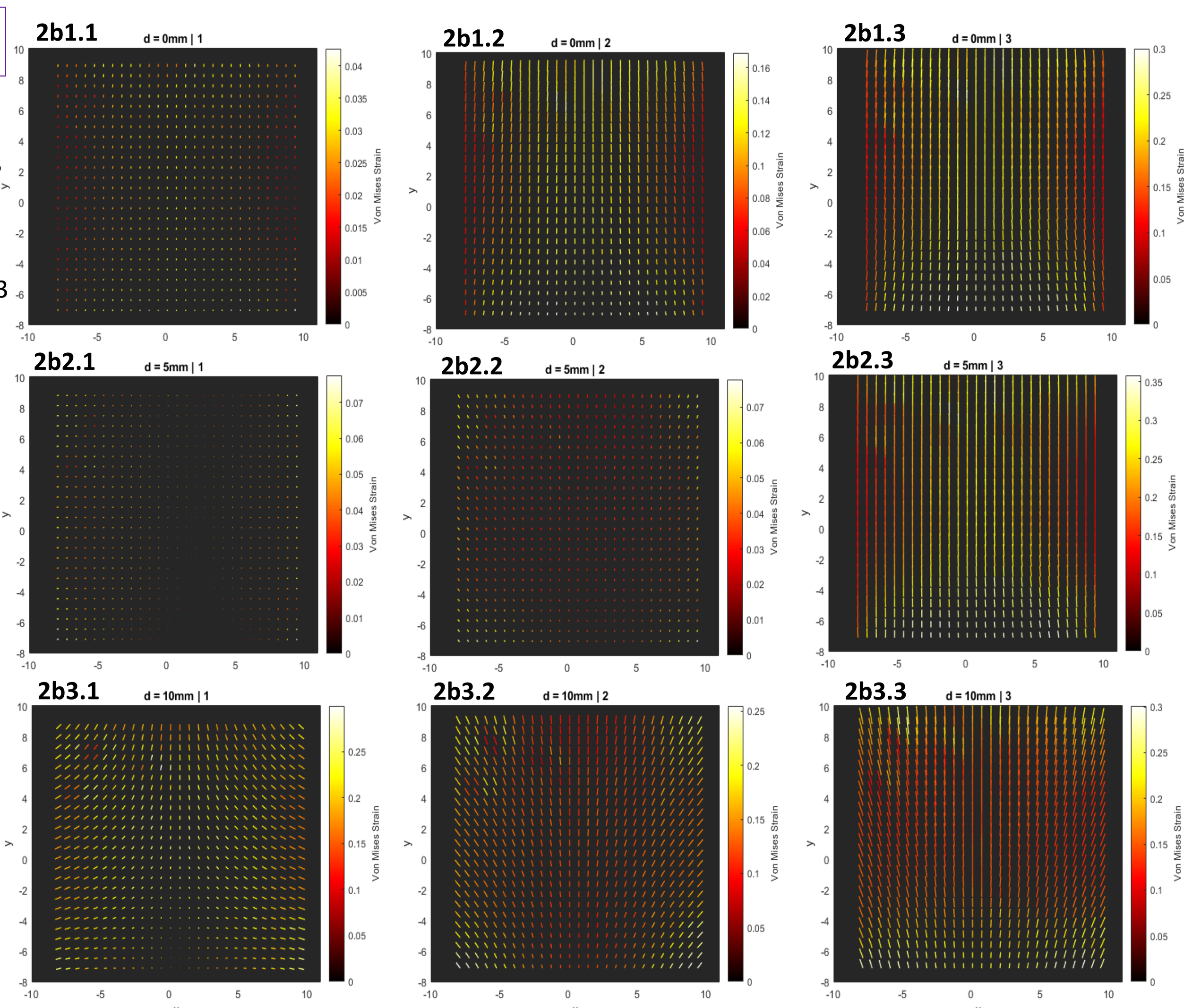


Figure 1 (Above): *The maximum F_{lo} developed for each l/L tested with different lateral displacements, d. There is an overall increase in force, indicative of increasing stiffness and as d is increased this maximum force is lowered.*

Figure 2a (Below): *DIC data showing the time evolution of central strains of the aponeurosis. Note the increasing convexity of the Von Mises curve with increasing d creating quadratic behaviour. Markers are correlated to vector plots in 2b*

Figure 2b (Below): *Vector plots showing displacement of DIC nodes. Vectors are coloured by Von Mises stress. With higher d, the Von Mesis strain development is more complex, with rotations in displacement. Note the variable strain scale between frames.*





DISCUSSION

- Increasing non-linearity in central strains planar to deformation may suggest missing strain directions in data.
- Reduction of apparent cross sectional area in the aponeurosis region may play a role missed by DIC.
- In comparison to biological tendon/aponeurosis tissue, with high anisotropy and multiple space/time scale dynamics, silicone is isotropic and hyperelastic. This may reduce the similarities in behaviour between biological and engineering models.

CONCLUSION

- Data suggest that laterally loading silicone elements induces variable stiffness in silicone.
- Shows an inverse longitudinal stiffness trend when compared to biological analogs.
- DIC Results suggest complex Von Mises strain development in the model aponeurosis.

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