Muscle coordination for generating natural “cascading” flexion of the fingers: Implementation in a biorobotic finger

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INTRODUCTION

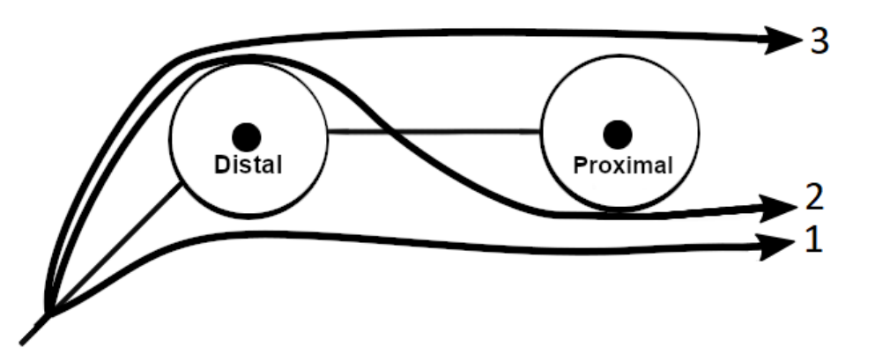
Restoring the coordinated flexion of the joints of the human fingers (i.e., cascading) [4] is critical to neurorehabilitation in stroke and other neurological conditions, and tendon transfers in spinal cord injury. This coordinated movement approximates an equiangular spiral trajectory, in which flexion of the interphalangeal joint angles progress equally during flexion. This is a foundation of the ability of the hand to delicately and precisely manipulate objects for quality of life [4, 1, 3]. Importantly, this movement is easily disrupted in neurological conditions and paralysis, demonstrating that careful muscle coordination is crucial [3, 6]. Current robotic analogs of human fingers aim to reproduce the equiangular spiral through fixed mechanical coupling of the system [7] as per the extensor mechanisms and Landsmeer's ligament [2].

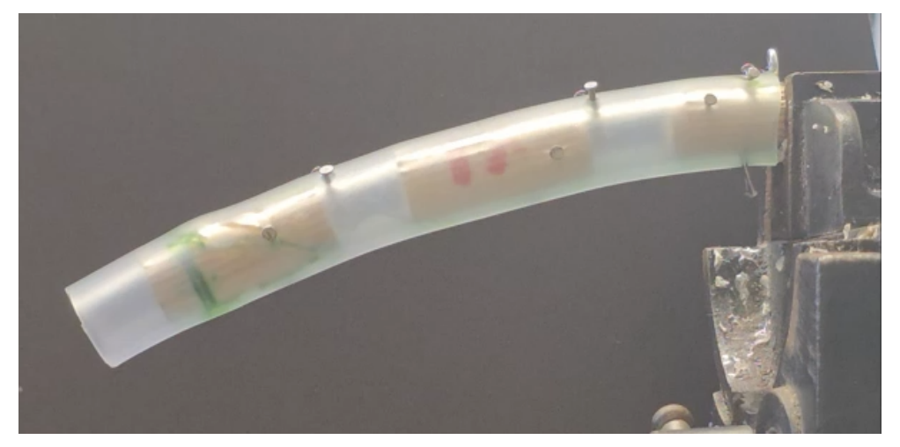
Objective

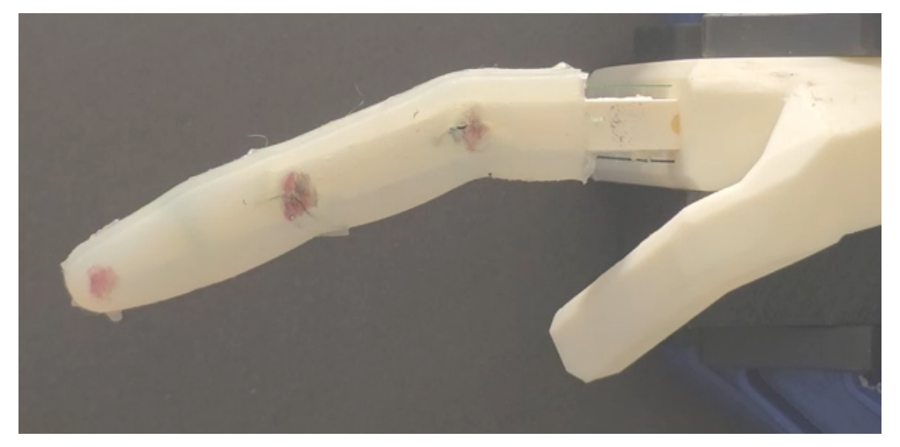
To create a hardware system to investigate the role muscle coordination plays in generating the **equiangular spiral** observed in human fingers.

MATERIALS AND METHODS

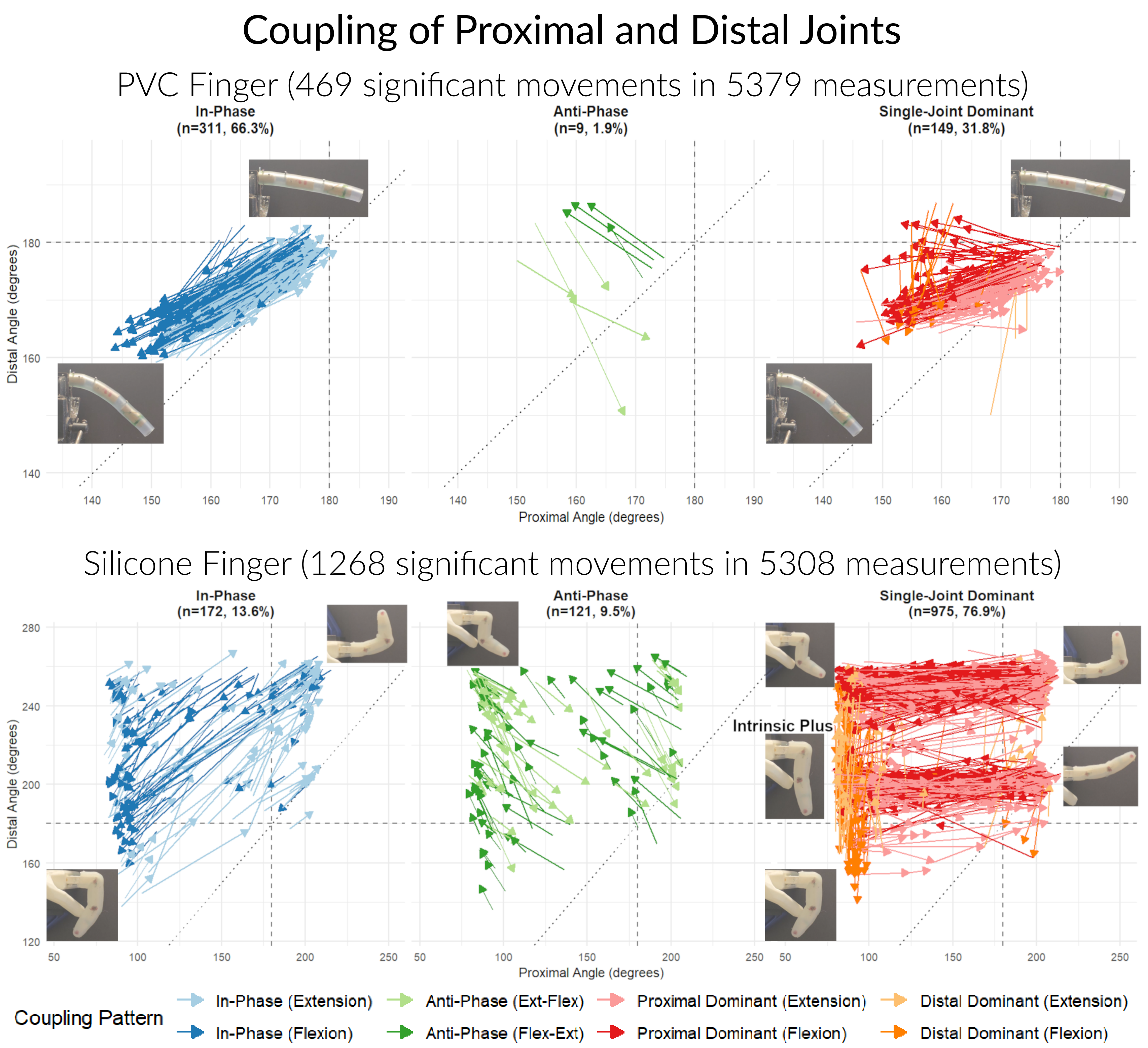
- We developed two 13cm, tendon-driven semi-soft fingers:
  A soft **PVC Finger** comprised of three 4cm wooden phalanges with 2cm of air between them, which served as joints. The wooden phalanges were fixed in PVC tubing.
  A **Silicone Finger** with 4 cm plastic phalanges. These rigid links were encapsulated in silicone.
- Tendons were routed per the N+1 design [5] where N is two degrees of freedom. Tendons are routed to cross and thus actuate multiple joints simultaneously.
- We define the equiangular spiral as a coupling angle of 225 degrees while flexion angles at interphalangeal joints are equal ($\angle J_1 = \angle J_2$).
- We generated sequences of random tendon activation sets and evaluated how close they lead to the finger approximating an equiangular spiral as we defined.
- We tracked markers on the fingers using Tracker by Open Source Physics.







RESULTS


Coupling of Proximal and Distal Joints

	PVC Finger	Silicone Finger
Convex Hull Area (deg^2)	920.86	15429.15
Total # of Tracked Frames	5379	5308
Total # of Movements with Magnitude > 10°	469	1268
In-Phase Movements (%)	66.3	13.6
Anti-Phase Movements (%)	1.9	9.5
Single-Joint Dominant Movements (%)	31.8	76.9

The silicone finger successfully demonstrated an expanded range of motion with a **15 times** larger joint-space compared to the PVC finger. However, this was accompanied by a **52.7%** reduction of In-Phase movements. The silicone finger strongly favored sequential, Single-Joint Dominant movements (**76.9%** of movements). Additionally, the silicone finger appears to have **five** states, one of which resembles the 'intrinsic plus' hand, as compared to the PVC fingers **two** states.

DISCUSSION

- Our results demonstrate that achieving coordinated movement is a challenge to **neuromuscular control** posed by **anatomical structure**. The difference in anatomical structure makes the silicone finger more difficult to control than the PVC finger.
- We believe the silicone finger's lack of compliant spacing creates a mechanical bias that favors proximal joint flexion. This bias appears seems to arise from progressively more resistance along the tendon path. In contrast, the PVC finger's gaps act as compliant elements enabling a more uniform tendon force transmission.
- This silicone finger model's flexion deficits resemble the 'intrinsic plus' finger deformity arising with weakness of the extrinsic muscles combined with spasticity of intrinsic muscles.
- Future work will test how reinforcement learning can generate policies for muscle control that can 'escape' mechanically favored postures. This will help understand deficits in neurological conditions and produce functional finger motions in tendon-driven robotic hands.

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