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The importance of Muscle Coordination in generating natural “cascading” of the fingers: Implementation in a biorobotic finger

Finger and Grasp Control: Human Behavior

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Abstract:

Objective: To investigate the role neuromuscular coordination plays in generating the equiangular spiral observed in human fingers.

Restoring the coordinated flexion of the joints of the human fingers (i.e., cascading, Littler, 1973) is critical to tendon transfers in spinal cord injury and neurorehabilitation in stroke and other neurological conditions. This coordinated movement approximates an equiangular spiral trajectory, in which the interphalangeal joint angles are equal during flexion. This pattern has been observed and described in both clinical and kinematic studies and is thought to underlie the hands' ability to delicately and precisely manipulate objects (Littler, 1973; Gupta et al., 1998; Kamper et al., 2003). Therefore, it is critical to quality of life. Current robotic analogs of human fingers aim to reproduce the equiangular spiral through the mechanical properties of the system (Wang, Freris, and Wei, 2025), and implementation of kinematic coupling as per the extensor mechanisms and Landsmeer ligament (Hentz & Leclercq, 2002). However, human fingers do not follow the spiral perfectly with every grasp, and the movement is easily disrupted in neurological conditions and partial paralysis, demonstrating that muscle coordination is crucial (Kamper, et al., 2003; Valero-Cuevas & Hentz, 2002). We aim to investigate the role of neuromuscular mechanisms in generating this characteristic pattern in a semi-soft biorobotic finger.

We developed a 12cm tendon-driven, semi-soft finger with 4 cm link lengths. These rigid links were encapsulated in silicone to mimic a human finger, hence ‘semi-soft.’ Tendons were routed per the N+1 design (Valero-Cuevas, 2016), a strategy where N represents the degrees of freedom (here, two). Tendons are routed to cross and thus actuate multiple joints simultaneously. We define the equiangular spiral as a movement such that the flexion angles at interphalangeal joints are equal ($\angle J1 = \angle J2$). We use a Reinforcement Learning (RL) algorithm to find sequences of tendon activation sets that lead to the finger approximating an equiangular spiral as we defined. Our null hypothesis (H0) posits that no such tendon activation pattern exists — supporting the emphasis on the mechanical design of human fingers to replicate this motion. The alternative hypothesis (H1) proposes that at least one pattern approximates the equiangular spiral. We anticipate that our RL algorithm will identify a narrow, brittle, path of optimal neuromuscular

control capable of generating the characteristic equiangular spiral—thus explaining its common clinical emergence.

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