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Rigid Robotic Transformations with Variable Link Lengths can approximate The Kinematics of Soft Fingers with ‘bones’

Device Technologies and Biomedical Robotics

Authors:

Nathan J. Matharu, Jan E. Lao, Timothy Fanelle, Suraj Raja, Francisco J. Valero-Cuevas

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Abstract:

Introduction:

Control of the endpoint location of a traditional hinged finger with rigid links is well established. Soft fingers can adapt their movements and grip on objects (Deimel and Brock, 2015), but controlling their kinematics accurately remains an open problem for soft robotic fingers on account of their (technically) infinite degrees of freedom (DOFs) (Santina et al., 2023). Semi-soft robotic fingers are a practical compromise, where the links are rigid but the joints are compliant (as in anatomical joints and Swanson silicone implants) (Alnaimat et al, 2021). Here we construct inexpensive semi-soft fingers by inserting rigid segments into a flexible PVC tube, and actuate them with four tendons (Figure 1), to test the the relationship between softness of the fingers (i.e., shorter segments make it softer) and the endpoint prediction accuracy to explore their future utility and select proper segment lengths in semi-soft hands. This study will allow us to build inexpensive yet controllable hands that have acceptable kinematic control.

Tendons were routed per the N+1 design (Valero-Cuevas, Fundamentals of Neuromechanics, 2016) where N is 3 degrees of freedom, in which tendons cross, and therefore affect multiple joints. Motors pulled on tendons with seven activation sets to drive the finger to different flexion-extension positions. The resulting finger endpoints were measured at each position using the DeepLabCut motion tracking software (Mathis et al., Nature Neuroscience, 2018). To test the validity of the linear rigid robotic transformations for our semi-soft finger, we calculated a linear regression relating endpoint locations to the seven tendon excursion sets.

Materials and Methods:

The semi-soft fingers (Figure 1) are constructed from wooden dowels with a diameter of 12.7 mm and flexible PVC tubes with an Inner Diameter of 12.7 mm and an Outer Diameter of 19.05 mm.

The wooden dowels are cut to lengths from 1cm to 4cm in increments of 1/2 cm and actuated by four tendons pulled by brushed DC motors (Jalaleddini et al, 2017). The total length of the finger is always 20 cm.

A markerless computer vision at 30 images per second (DeepLabCut™) and MATLAB predicted joint centers and joint angles during flexion movements. We measured the endpoint location directly from the images during 16 flexion movements starting from fully-extended

posture created by the 16 activation sets consisting of the permutation of 0 or 1 to each of the four motors, each set repeated twice to produce two flexion movements. We calculated the maximal error in the planar location of the endpoint (Euclidean distance between actual and predicted) compared to two analytical methods (that could be used in future controllers): (1) constant link lengths and (2) compressible link lengths. In both cases, we used the standard kinematic model for a 3-link, 3-DOF planar finger (Valero-Cuevas, 2016), with the difference that in (1) we held link constant as per the start of the movement or calculated at every time point (as the tube at the joints compressed under tendon actions).

Results, Conclusions, and Discussions:

Results:

The goal of our study was to quantify how the “softness” of semi-soft fingers affects the accuracy of kinematic predictions of the endpoint location of a finger during a flexion movement.

We find that a kinematic model that updates the measured link length at every image sampled can best predict the endpoint location (Figure 2). Assuming constant link lengths for this type of semi-soft finger produces prediction errors that were up to 3—5 times larger, for all dowel lengths. The kinematic model with adjusted link lengths has a maximum prediction error between 5.20 mm and 15.78 mm — a 74% error reduction on average.

While we only report the maximal prediction errors, detailed results show that the errors are larger when assuming constant link lengths throughout the movement.

Naturally, as dowels become shorter the error increases (as more of the effective link length is soft). However, the slope of this increase in error is smaller when adjusting effective link lengths.

Discussions:

Our results show that semi-soft fingers can be a good compromise to fully rigid or fully soft fingers as they retain the ability to conform to object shape while allowing relatively accurate endpoint location predictions.

The present study used a planar, 2-dimensional model, but future studies should investigate 3-dimensional models to determine if the same linear equations can predict link lengths.

Additionally, this approach uses computer vision to predict link lengths, which is susceptible to occlusions. Future studies should attempt to utilize machine learning to overcome this limitation.

Conclusions:

This study has sucessfully constructed a cost-effective semi-soft robotic finger whose endpoint can be accurately predicted within 6mm for planar flexion motions. This opens up exciting possibilities for well-controllable, yet compliant, robotic hands that approximate the utility of the human hand, which is itself semi-soft.

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Figures:

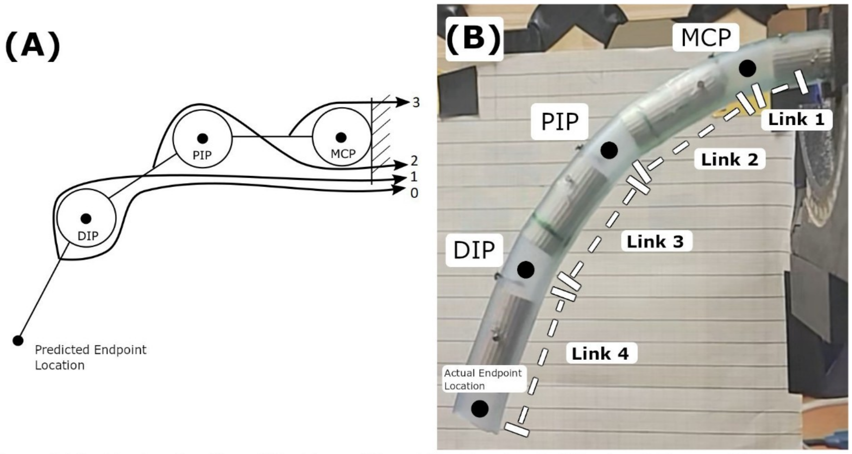

Figure 1. The Tendon Routing of the Finger (A) and the Constructed Semi-soft Finger with 4cm Bones. MCP: Metacarpophalangeal Joint. PIP: Proximal Interphalangeal Joint. DIP: Distal Interphalangeal Joint.

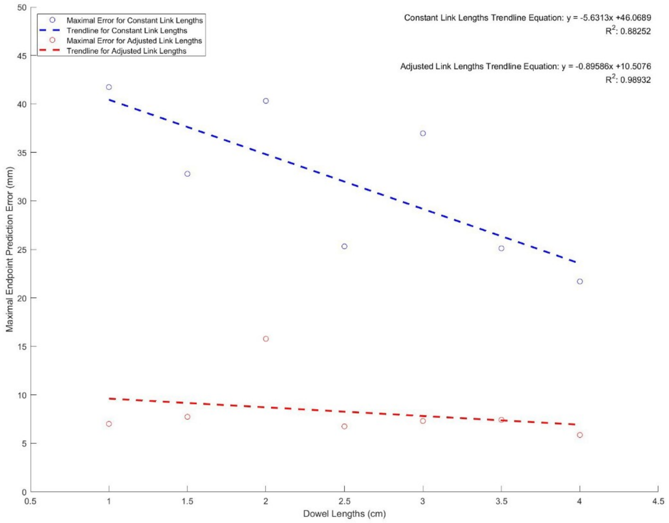

Figure 2. Maximal Kinematic Prediction Error When Link Lengths are Held Constant and When Link Lengths are Adjusted

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