Control of muscle strain energy as a robust means to produce slow and accurate finger movements: Proof of concept via hardware and cadaver implementation

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Motivation

The neural control of finger movements is unknown.

Existing motor control hypotheses have not been tested on realistic systems approximating the structure of the anatomical hand.

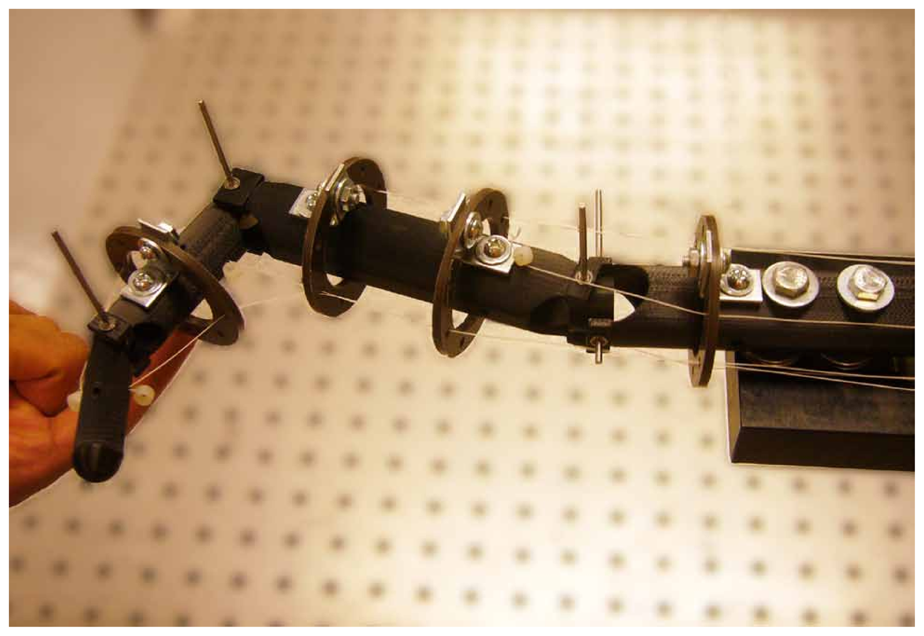
To test these hypotheses, we created a computer-controlled system to drive a mechanical finger and human cadaveric fingers [1].

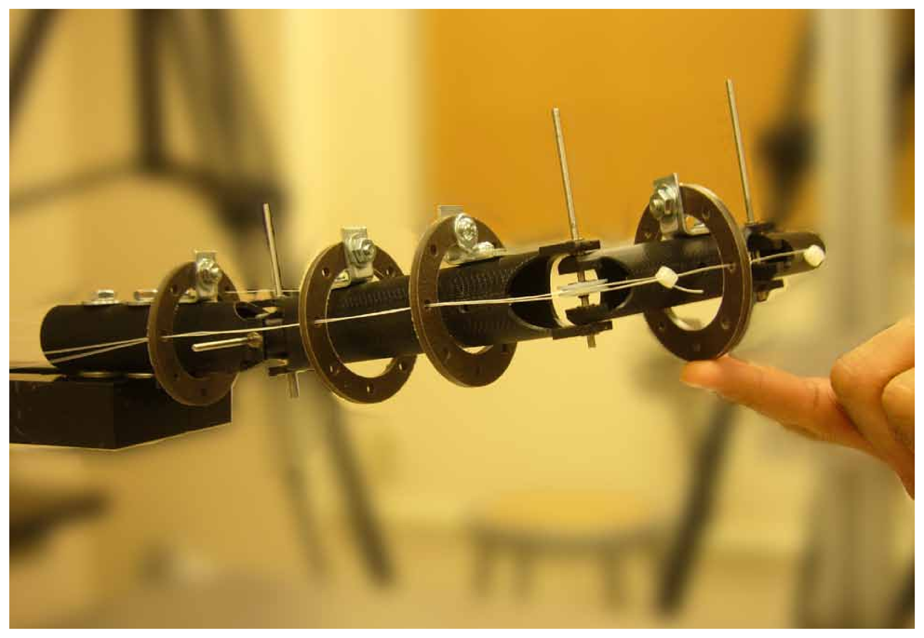
We tested two commonly-proposed motor control strategies:
Force control: a low-level controller applies a given force pattern to the tendons,
Strain-energy control: a controller sets the rest lengths of muscles, here, simulated as Hookean springs.

[1] Valero-Cuevas FJ, Towles JD, and Hentz VR. J Biomech 33: 1601-1609, 2000.

Setup

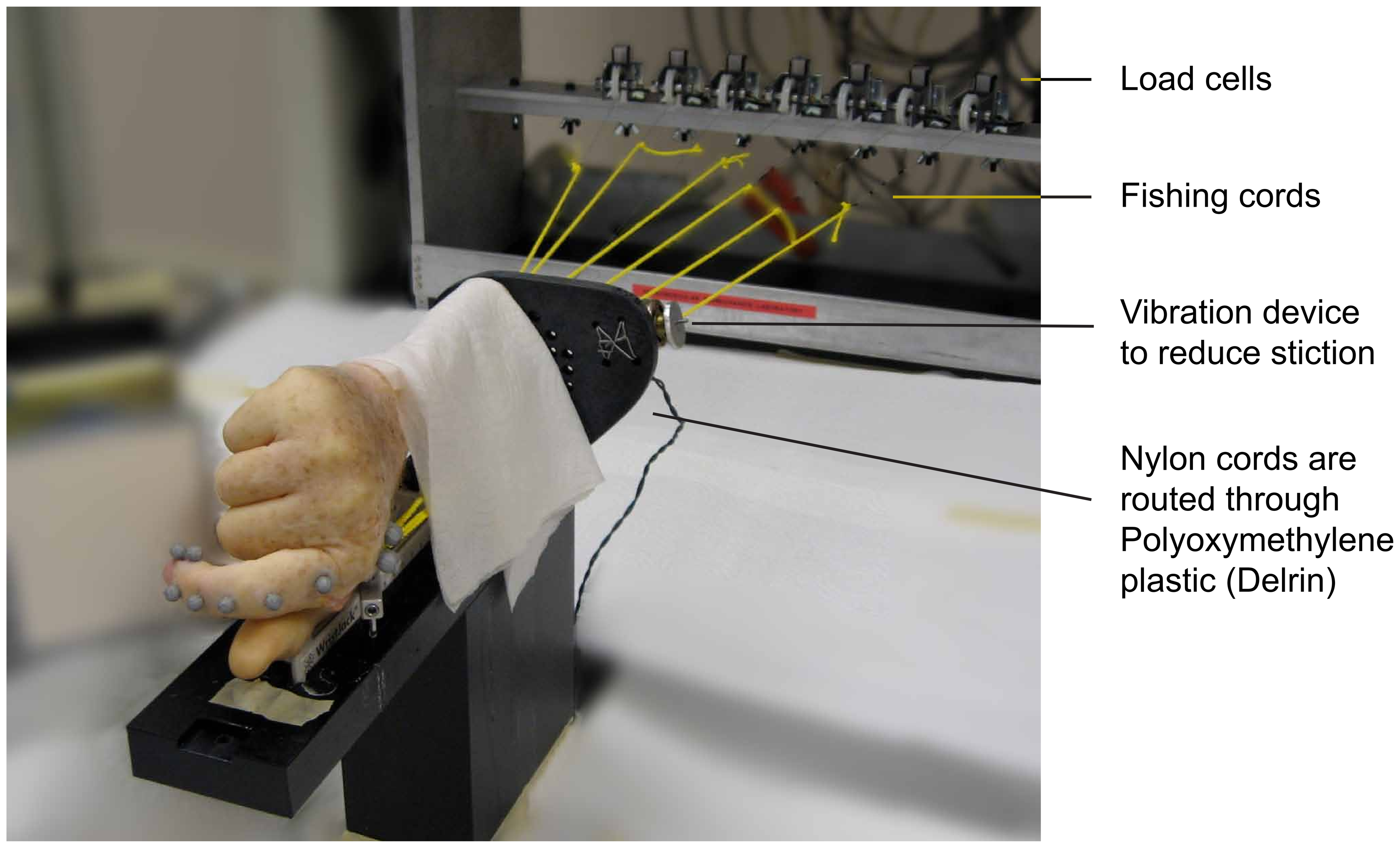
The computer-controlled system drives seven motors, each connected to a spindle. Strings winding on the spindles pull either on a mechanical finger or on all seven tendons of a human cadaveric index finger. Real-time feedback is measured for each tendon's force and excursion.





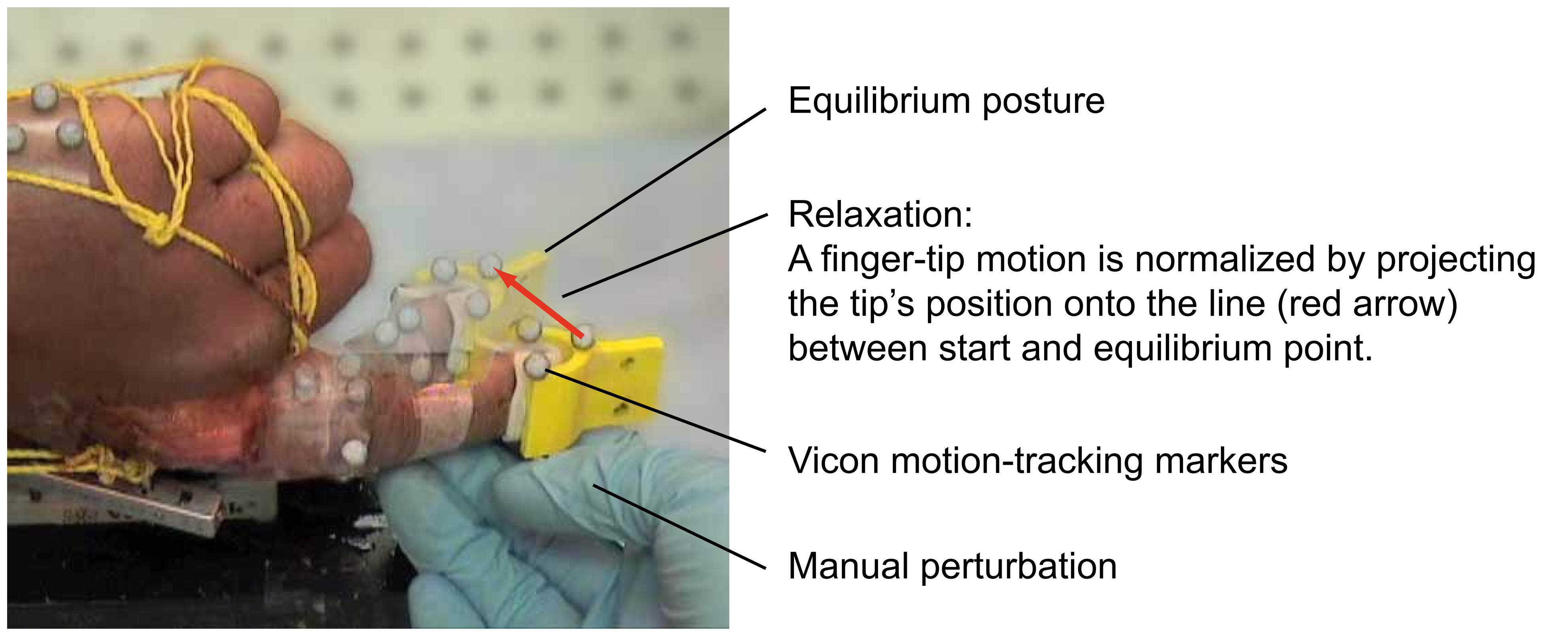
The four-degrees-of-freedom mechanical finger is equipped with polyoxymethylene disks that allow alternative tendon-routing paths. We mimicked the main routing paths in the index finger.

The cadaver hand is mounted on a wrist jack, which fixed the metacarpal and radius bones.



Perturbation Experiment and Results

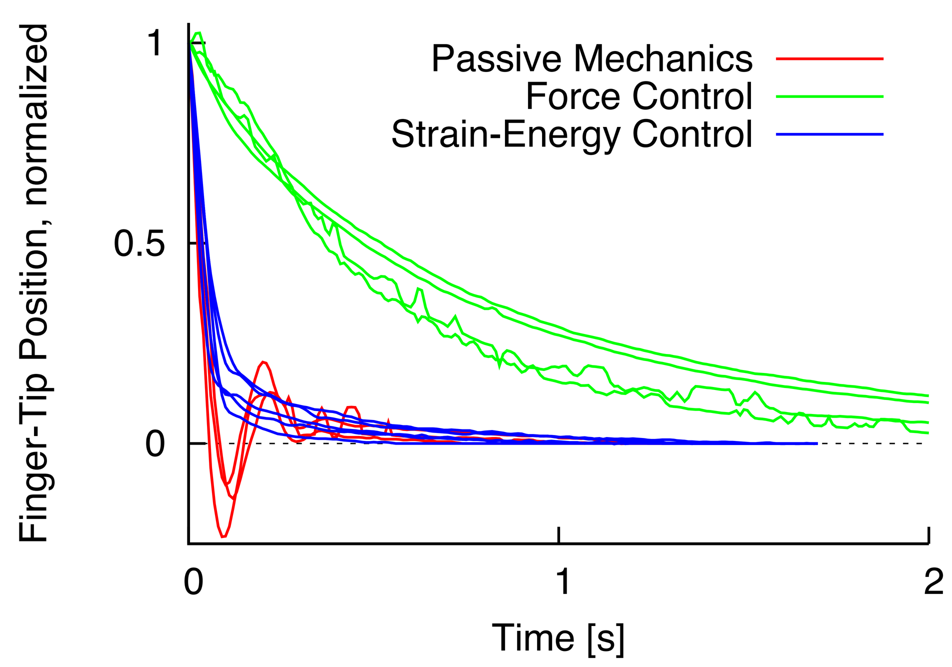
Under force or strain-energy control, the cadaveric index finger was manually perturbed and the resulting reaction observed.



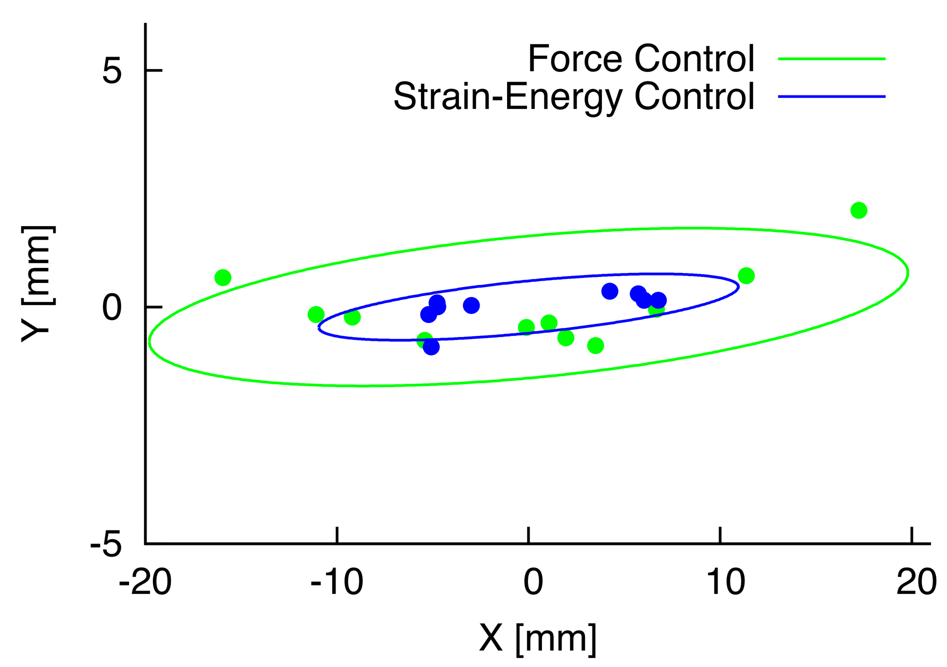
Force Control: Pulling force on both extensor tendons: 8 N, on the other five tendons: 2 N

Strain-Energy Control: Spring stiffness on all seven tendons: 3 N/mm, Initial strain: 1 mm

Perturbation Reaction



Distribution of Convergence Points



Relaxation Times

Force Control: 0.69 ± 0.13 s (mean ± SD, n = 4)
Strain-Energy Control: 0.063 ± 0.017 s (n = 5)

Dots are points of convergence of the finger tip after single perturbations. Ellipses show boundary of 95% variance.

Conclusions

We have a new paradigm to compare and contrast alternative neural controllers, while fully considering the anatomical complexity of the hand.

Strain-energy control was more robust than force control, reacting faster to perturbations and having lower hysteresis. In the mechanical finger, we could not stabilize desired postures using constant force patterns.

The hand biomechanics limit the number of feasible control strategies. A strategy that relies on a constant force pattern to result in a desired equilibrium point is infeasible.

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