All muscles are redundant, but some are less redundant than others

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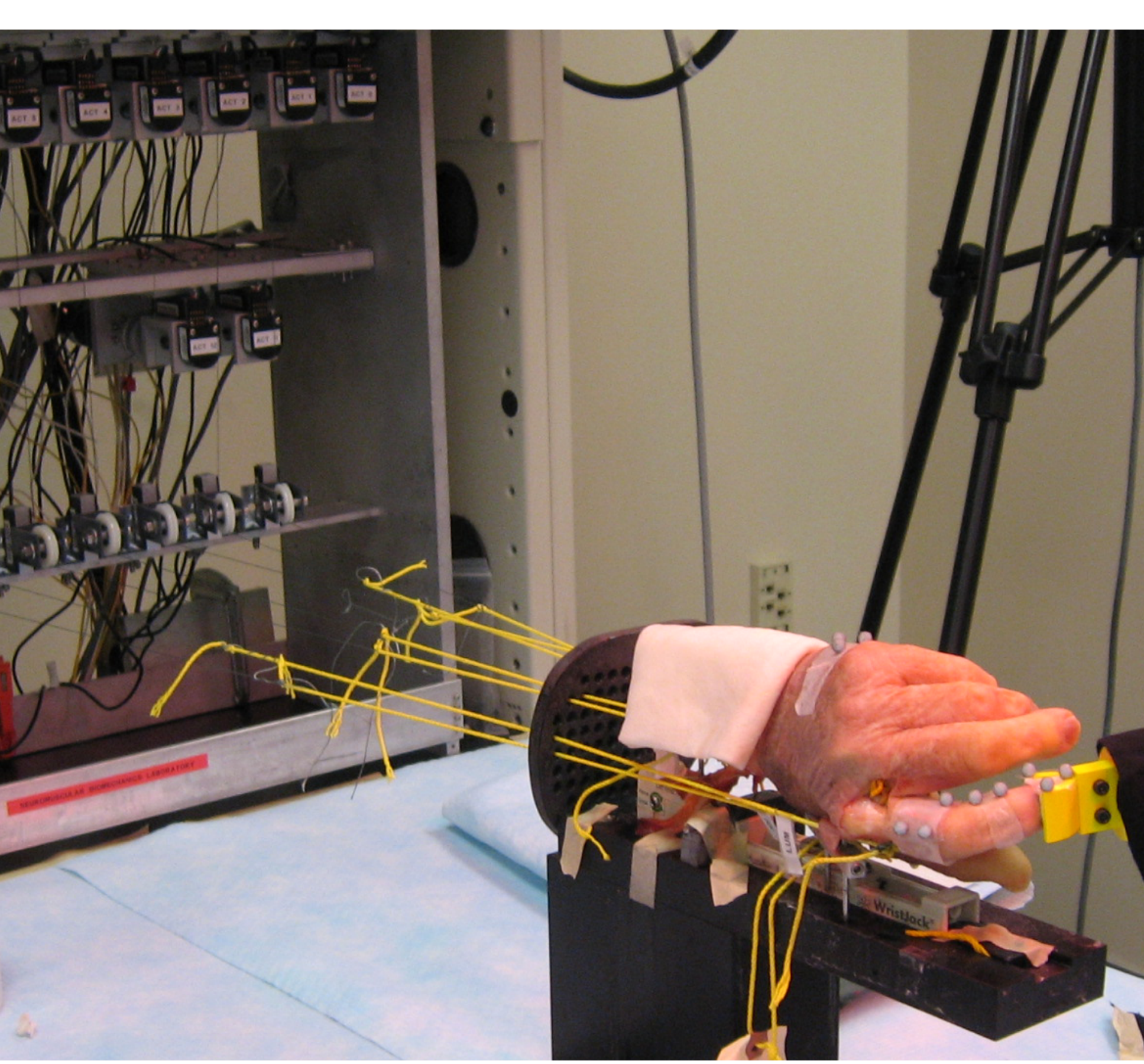

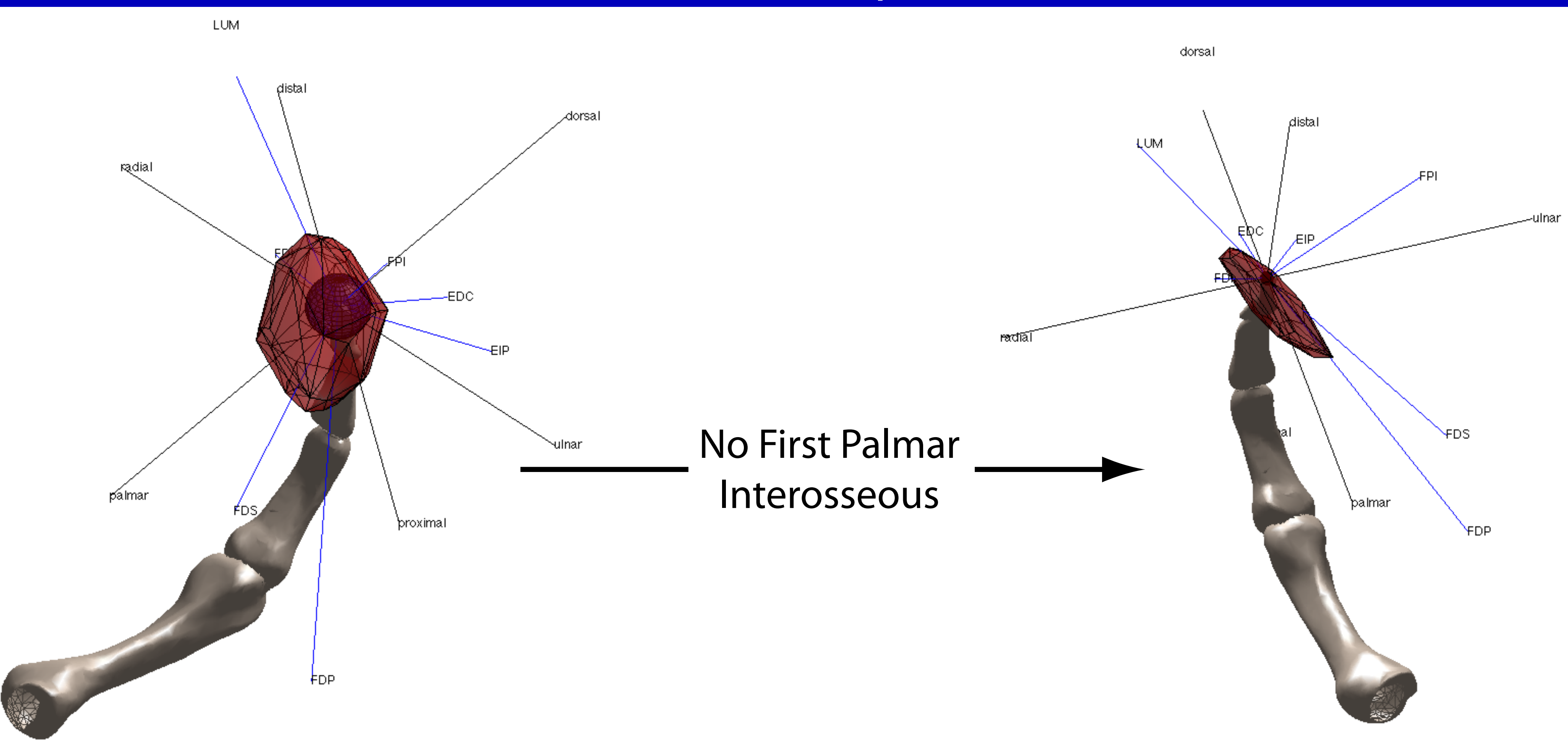## Introduction: Two distortions of the concept of muscle redundancy

1. If you lose a muscle, the other muscles can compensate

2. There is an infinite number of different combinations of muscle forces that will produce the same joint torque

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Analyzing redundancy: the vertex enumeration problem

$$A = \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ 1 & 0 \\ 0 & 1 \\ a_1 & a_2 \\ -a_1 & a_2 \end{bmatrix} \quad b = \begin{bmatrix} 0 \\ 0 \\ \text{Musl 1 MVC} \\ \text{Musl 2 MVC} \\ -\text{Desired force} \\ \text{Desired force} \end{bmatrix}$$

Vertex enumeration solves for boundary of
$$b - Ax <= 0$$
and defines minimal and maximal force for each muscle in the task

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Experimental preparation and approach

1. Fresh cadaver arm resected at mid-forearm, dissected to reveal tendons for index finger.

2. Tendon tensions computer controlled.

3. Index fingertip attached rigidly to 6 DOF load cell (JR3, Woodland, CA).

4. Feasible force set measured using all possible combinations of active and inactive muscles:
Input 1: [1,0,0,0,0,0,0] : Record JR3 reading
Input 2: [0,1,0,0,0,0,0] : Record JR3 reading
...
Input 7: [0,0,0,0,0,0,1] : Record JR3 reading
Input 8: [1,1,0,0,0,0,0] : Record JR3 reading
...
Input 127: [1,1,1,1,1,1,1] : Record JR3 reading
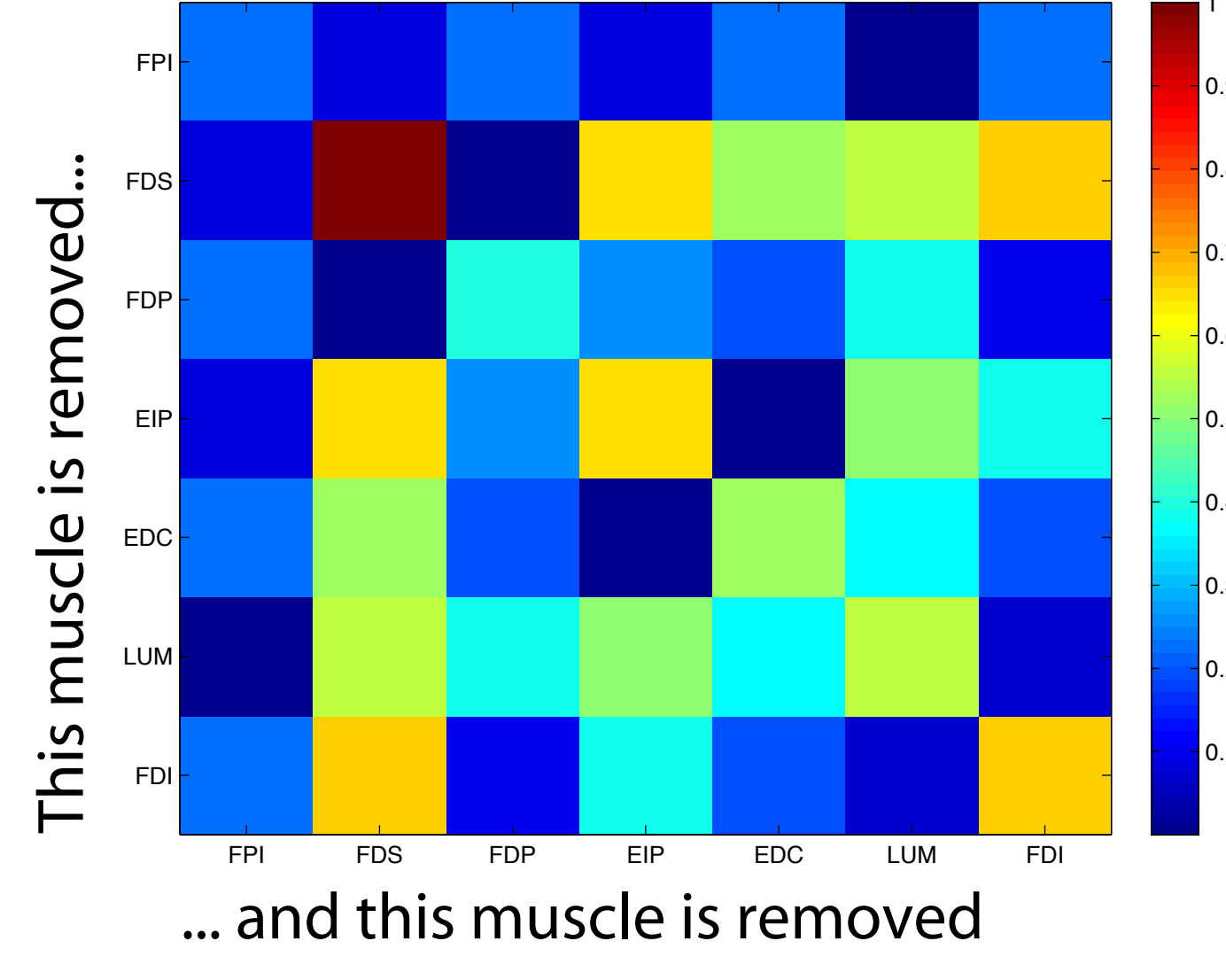1 = maximum tendon tension

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Fact Number 1: The feasible force set collapses

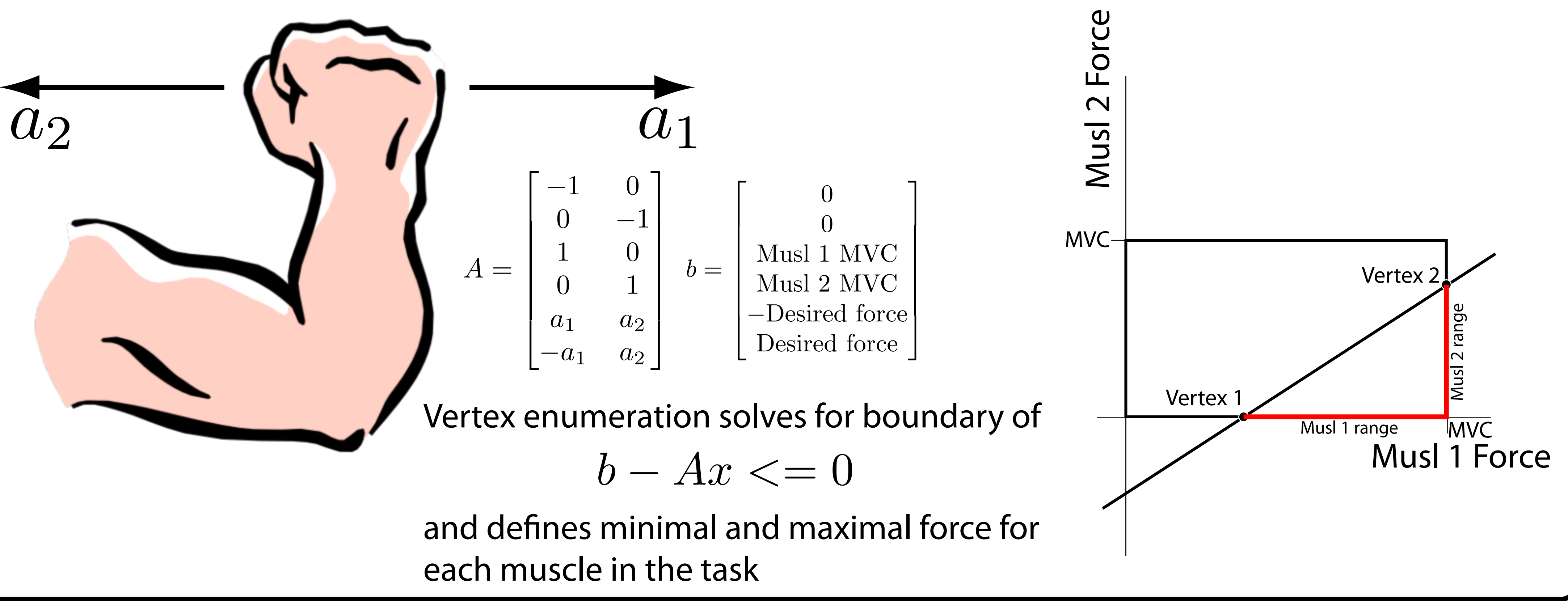No First Palmar Interosseous

Pairwise versatility reduction (fraction of original sphere radius)

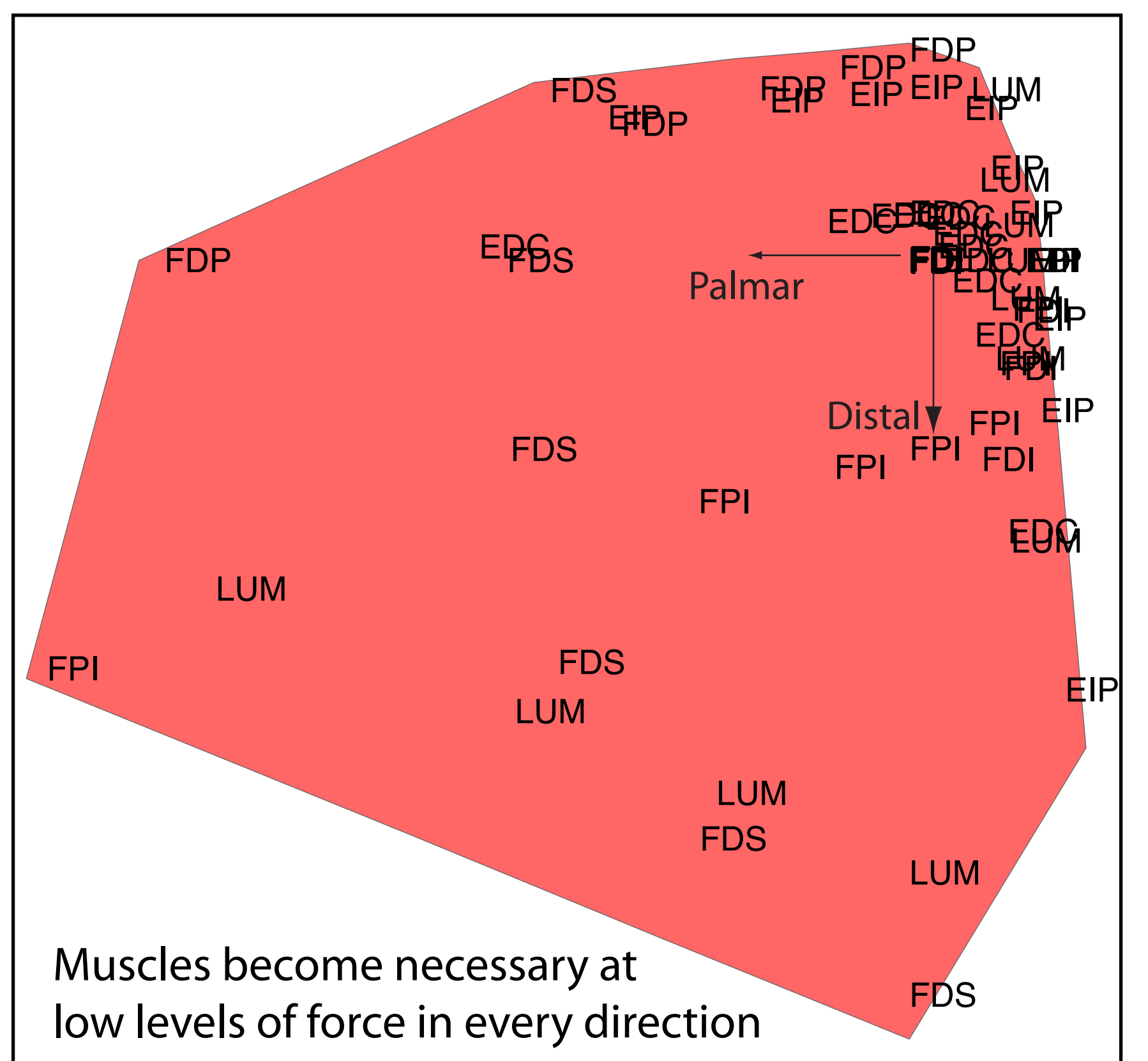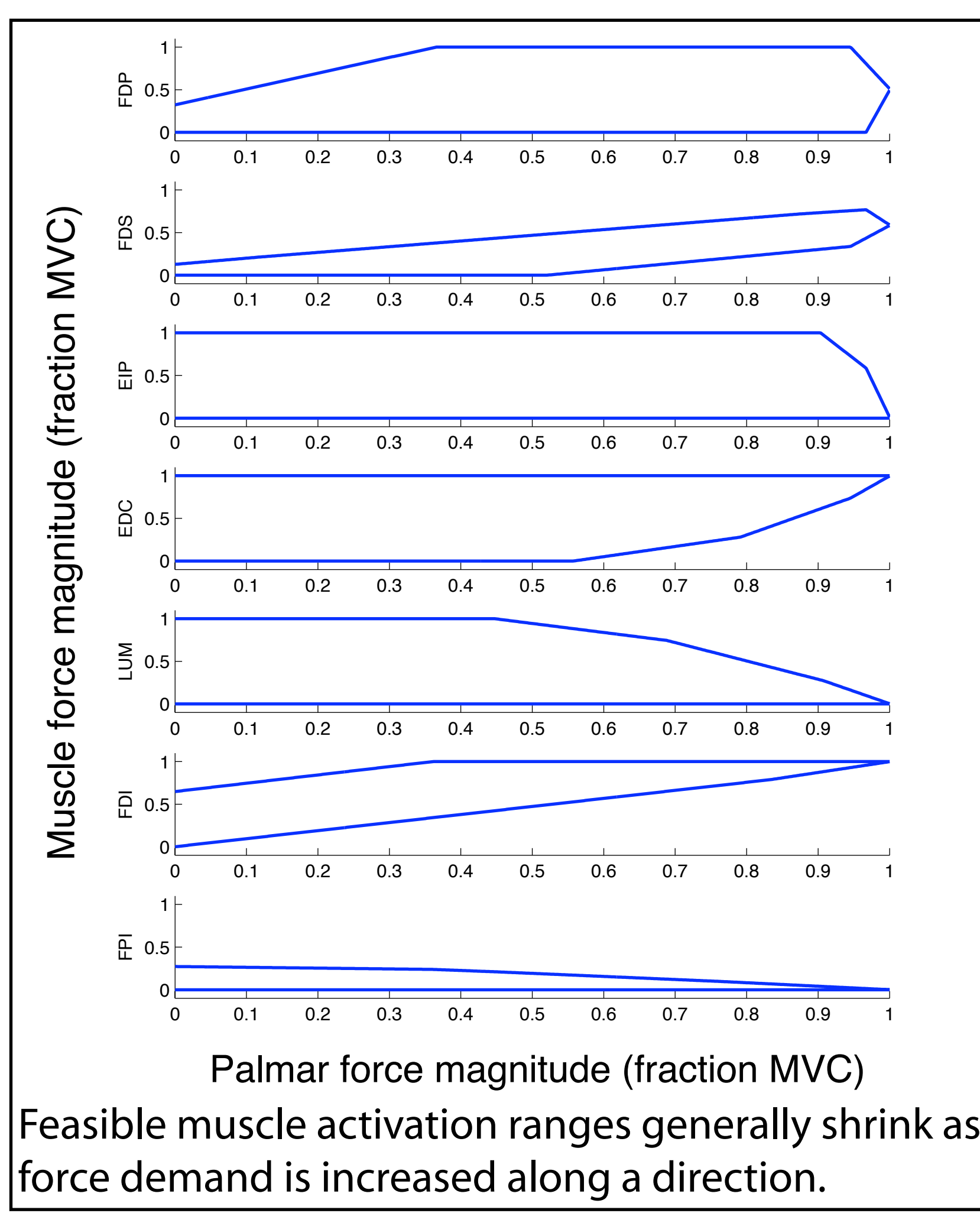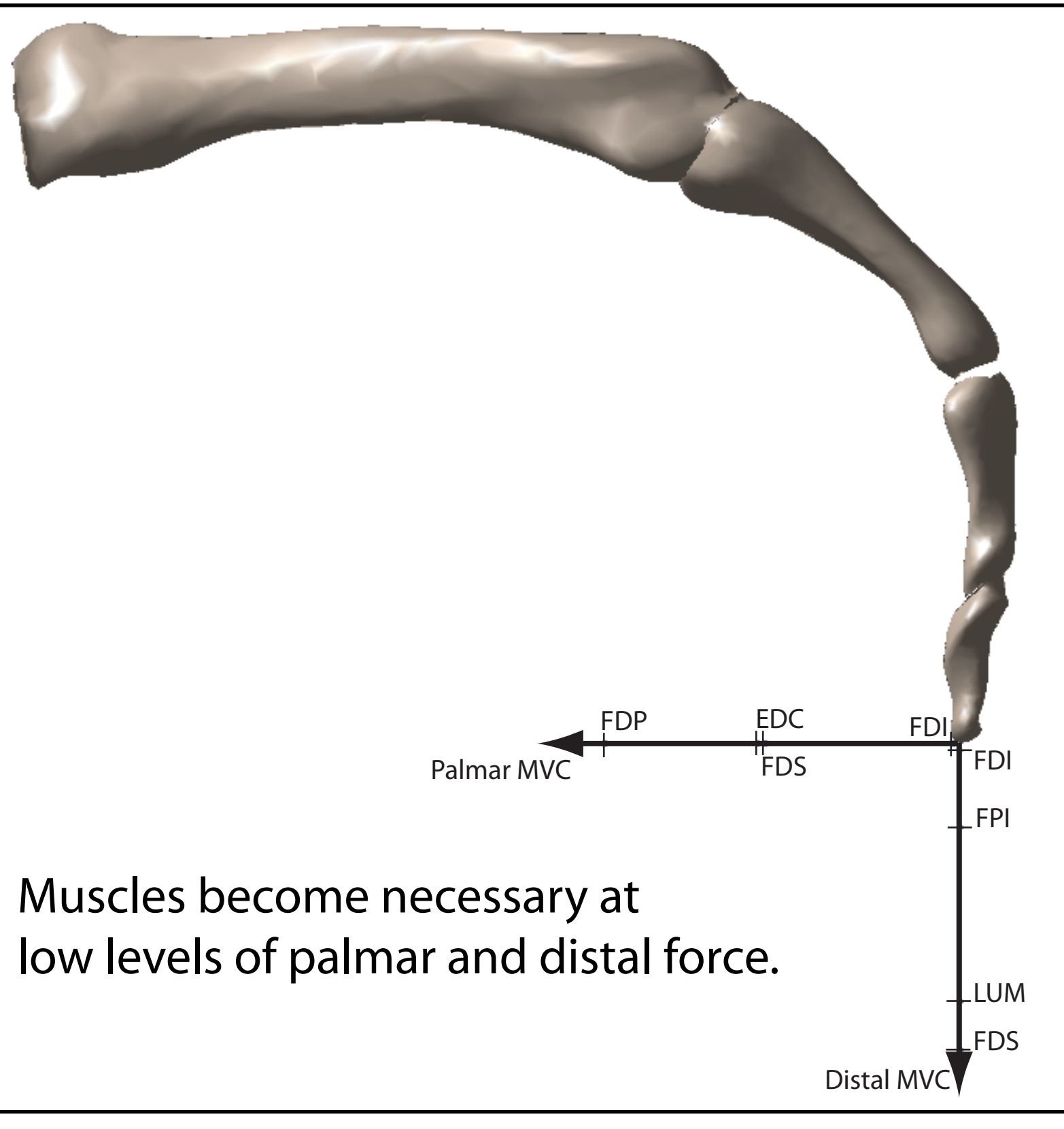This muscle is removed... ... and this muscle is removed

Loss of different muscle combinations can easily be simulated in the cadaver preparation. This matrix of color intensities shows how much less force can be generated in every direction in 3-dimensions when particular pairs of muscles are removed.

Fact Number 2: Strange muscles become necessary for submaximal force

Vertex enumeration reveals
1. FDI necessary for even the smallest forces
2. EDC/FDS required for >50% palmar force
3. FPI required for >30% distal force
4. Feasible activation ranges usually shrink for all muscles as force magnitude increases.
5. Different muscles become necessary in different force directions.

Muscles become necessary at low levels of palmar and distal force.

Muscle force magnitude (fraction MVC)

Palmar force magnitude (fraction MVC)

Feasible muscle activation ranges generally shrink as force demand is increased along a direction.

Muscles become necessary at low levels of force in every direction

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Conclusion: Can't assume muscles are redundant!

1. Just because the number of muscles exceeds the number of degrees of freedom doesn't mean that muscles are redundant.
2. Redundancy depends on musculoskeletal geometry - must be quantified.
3. The CNS may not have as much latitude in choosing muscle activiations as is usually assumed.
4. The muscular system is not robust to muscle weakness.

References
1. Bernstein, N.A. The Co-ordination and Regulation of Movements (Pergamon Press, Oxford, 1967).
2. Macpherson, J.M. How flexible are muscle synergies? in Motor Control: Concepts and Issues (ed. D.R. Humphrey & H.-J. Freund) 33-47 (Wiley Press, New York, 1991).
3. Valero-Cuevas, F.J., Towles, J.D. & Hentz, V.R. Quantification of fingertip force reduction in the forefinger following simulated paralysis of extensor and intrinsic muscles. J Biomech 33, 1601-1609 (2000).
4. Kuzhaus, L., Roach, S.S. & Valero-Cuevas, F.J. Quantifying deficits in the 3D force capabilities of a digit caused by selective paralysis: application to the thumb with simulated low ulnar nerve palsy. J Biomech 38, 725-736 (2005).
5. Valero-Cuevas, F.J., Zajac, F.E. & Burgar, C.G. Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. Journal of Biomechanics 31, 693-703 (1998).