"Myths and Monsters in Motor Control"

Part 1: Muscle redundancy Valero-Cuevas

Part 2: Henneman's size principle Kutch

Part 3: Optimal control and internal models Loeb

Part 4: Is optimal control a panacea? Theodorou

“Myths and Monsters in Motor Control”

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These are all difficult problems of scientific inference that are near and dear to us

Sort of like these...

1977

1967

c. 1930

c. 2010

Sort of like these...

1977

c. 1930

1967

c. 2010

Webarchive for this Panel Session

google “valero-cuevas” and navigate to “Events”

University of Southern California

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Prof. Francisco Valero-Cuevas

Brain-Body Dynamics Lab

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Myths and Monsters in Motor Control

21st Annual Conference of the Society for the Neural Control of Movement

Friday, April 29, 2011, 8:00 am - 10:15 am

Co-Chairs: Francisco J Valero-Cuevas and Jason J Kutch

Participants: Gerald Loeb and Evangelos Theodorou

Abstract: Progress in the field of Sensorimotor Neuroscience hinges on a clear and up-to-date understanding of its fundamental tenets. While the validity of these tenets is routinely discussed and debated in the literature, it is also necessary to present them to the community in a manner that challenges all of us to affirm, update or revise them. This is particularly true when challenges or revisions to these tenets hinge on the details of specialized computational approaches, a nuanced interpretation of multiple experimental findings, a thorough knowledge of a vast literature, integration of recent findings, and/or careful semantic distinctions. We have assembled a team of four investigators with relevant expertise to critically review four fundamental tenets in light of recent work:

1) Muscle redundancy; Valero-Cuevas

2) Henneman's Size Principle; Kutch

3) Spinal Circuitry for Motor Behavior; Loeb

4) Optimal Control; Theodorou

Part 1: Muscle redundancy

Francisco Valero-Cuevas
Brain-Body Dynamics Laboratory

University of Southern California

Over-, under-, or exact-actuation

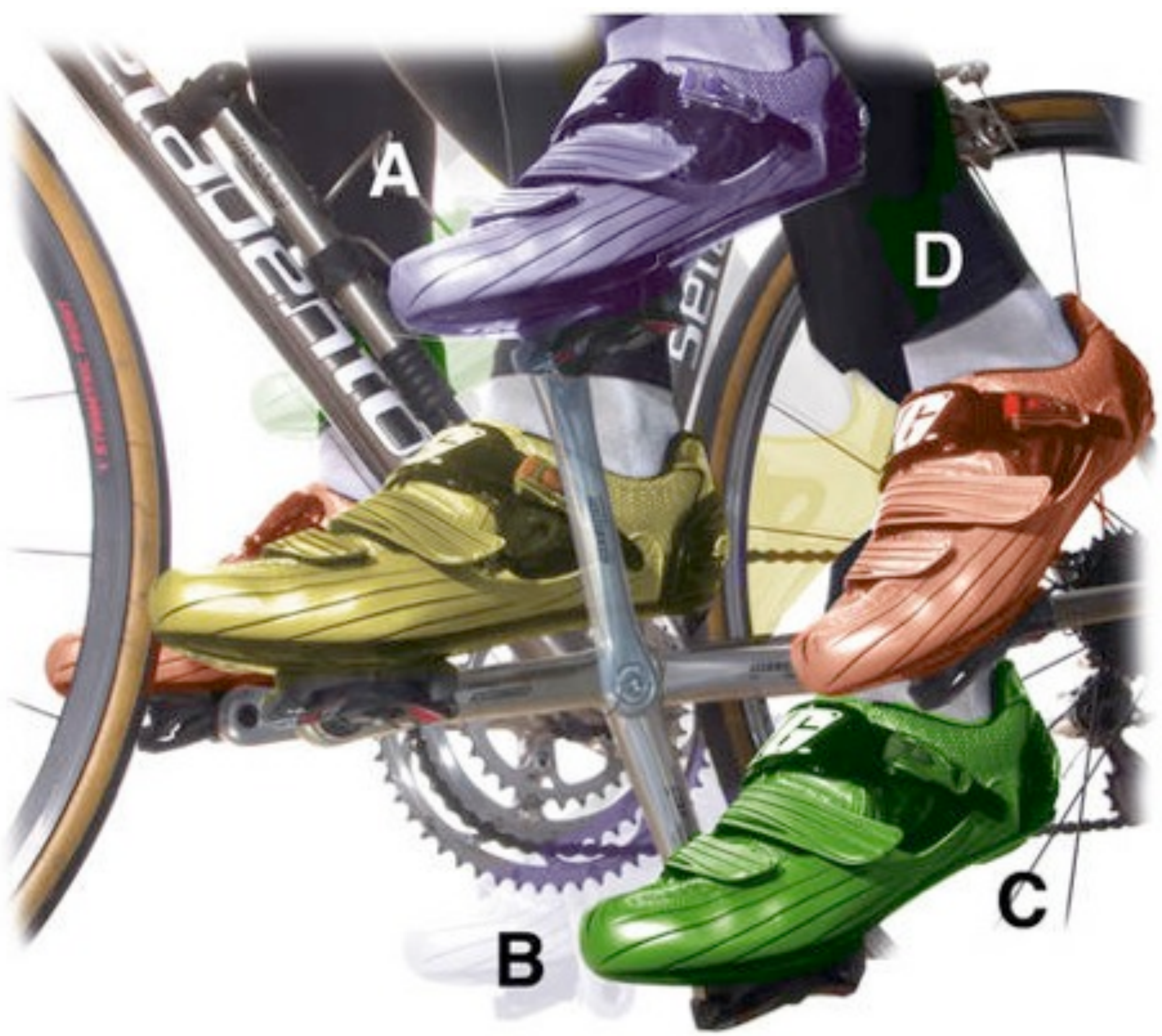
Often called the central problem of sensorimotor neuroscience.

I will discuss critical aspects of the control of tendon-driven systems such as versatility, redundancy, robustness and multi-muscle control.

One starting point:
A working definition of "versatility"

Simply put: the ability to produce end-point force in every direction.

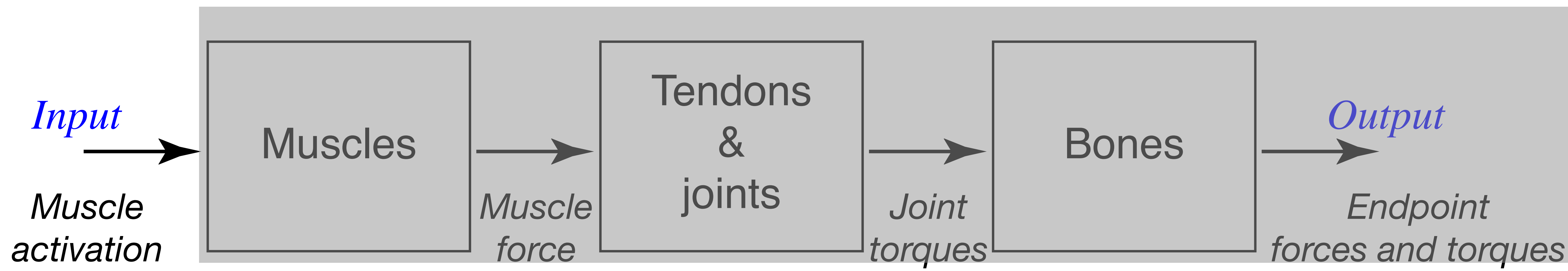
Not to worry, it can be extended to motion in every direction!



Valero-Cuevas. A mathematical approach to the mechanical capabilities of limbs and fingers. PMC V 2009.

The musculo-skeletal system "filters" the propagation of neural commands

Block diagram of transformations in a forward limb model



(activation space) (muscle force space) (torque space) (wrench space)

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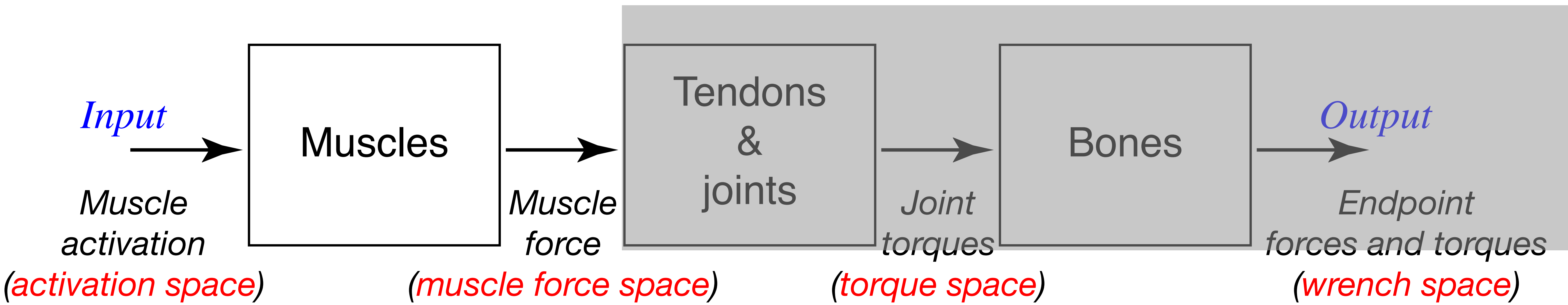

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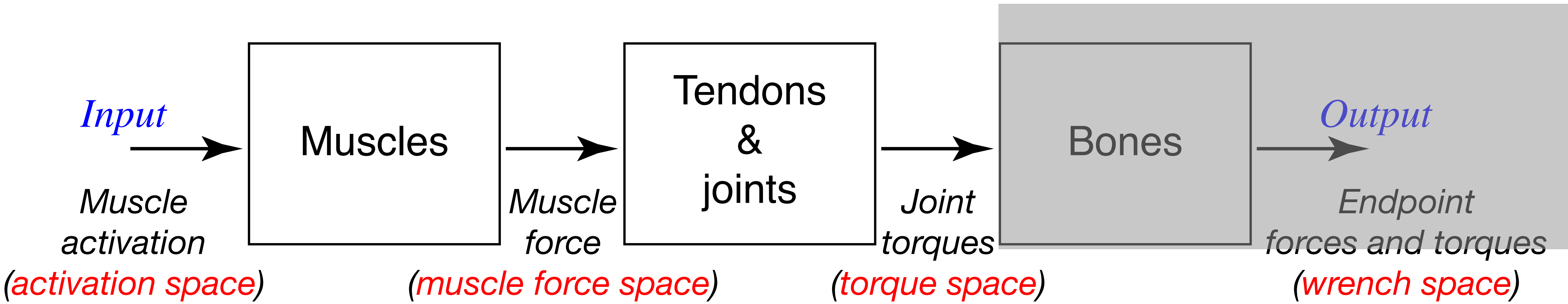

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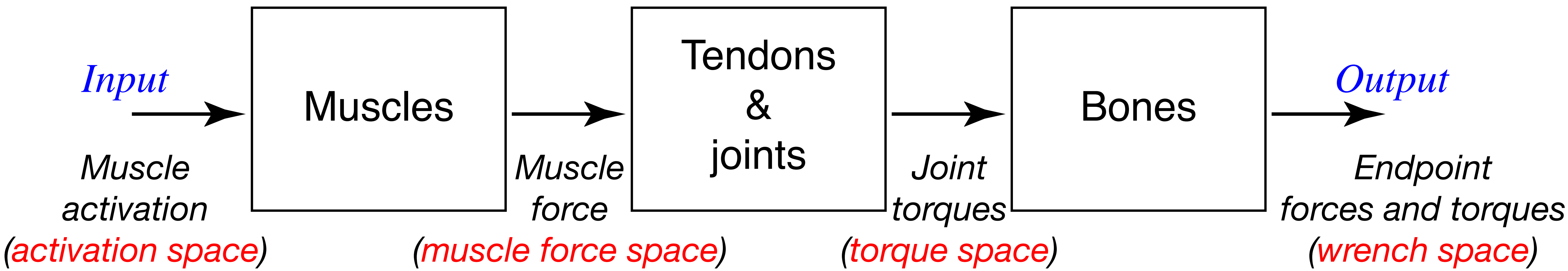

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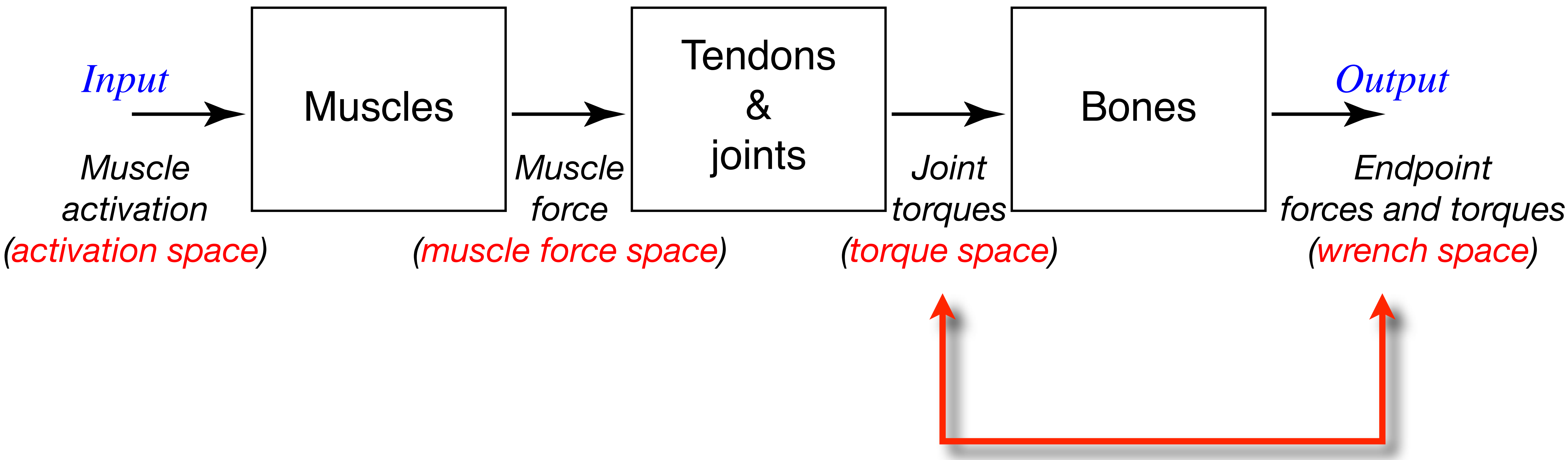
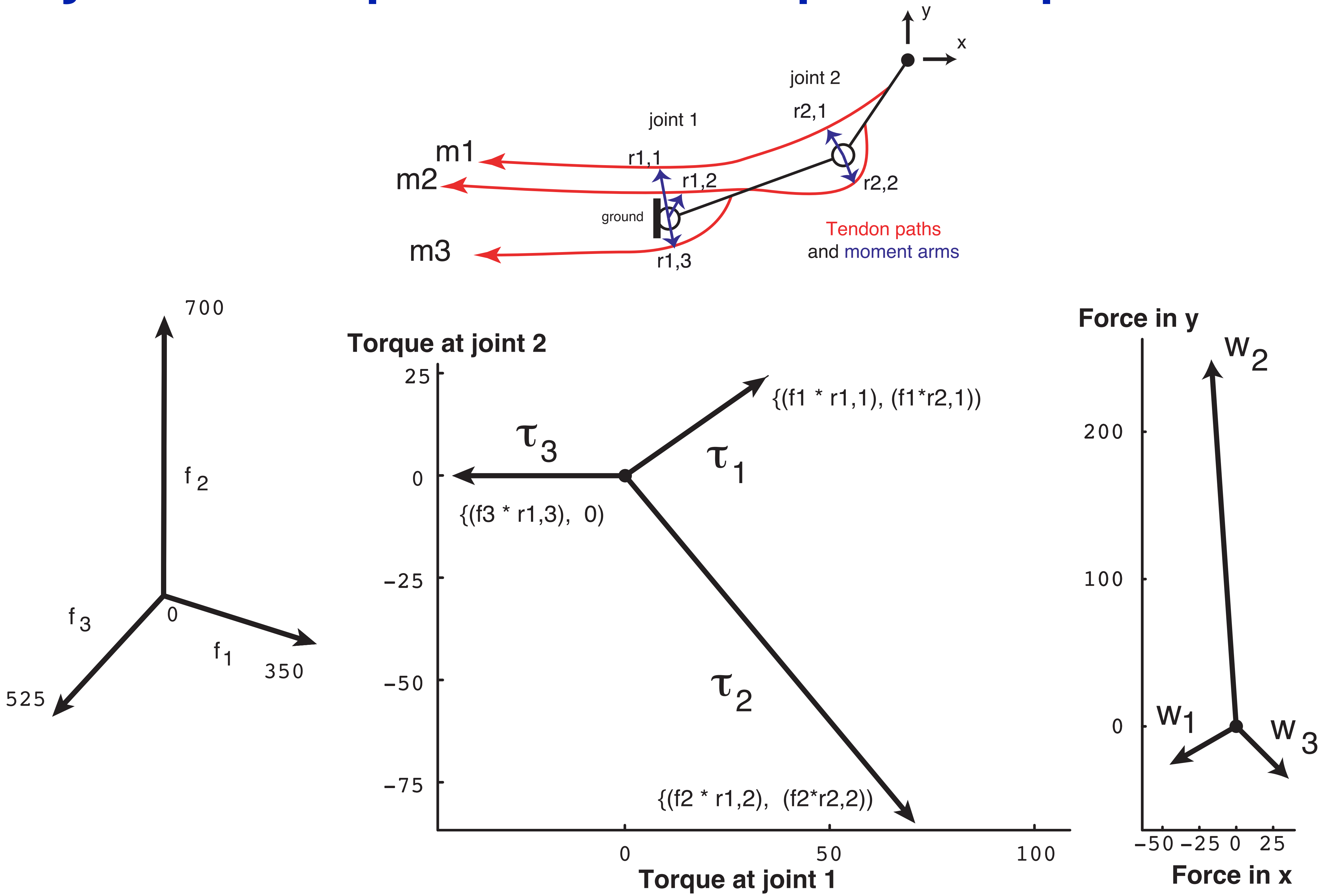


Producing end-point force in every Cartesian direction requires that you produce torques in every direction in "torque space"

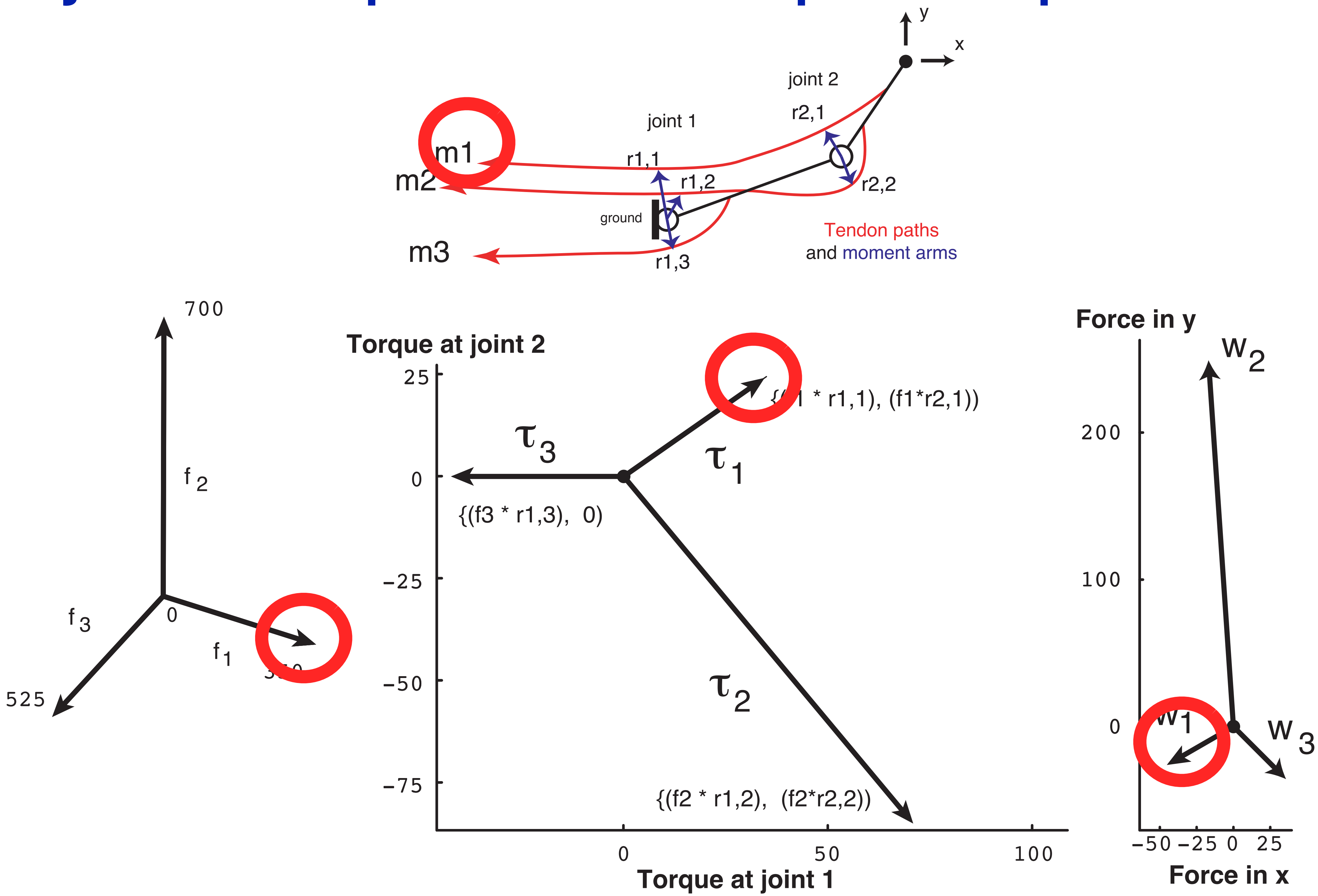
Muscle actions in joint torque and endpoint spaces



muscle force space (N) $\xrightarrow{\text{R matrix}}$ joint torque space (N-m) $\xrightarrow{J^{-T}\text{ matrix}}$ endpoint wrench space (forces in N)

Spoor, An, Yoshikawa, Brand, Leijnse, Valero-Cuevas, etc.

Muscle actions in joint torque and endpoint spaces



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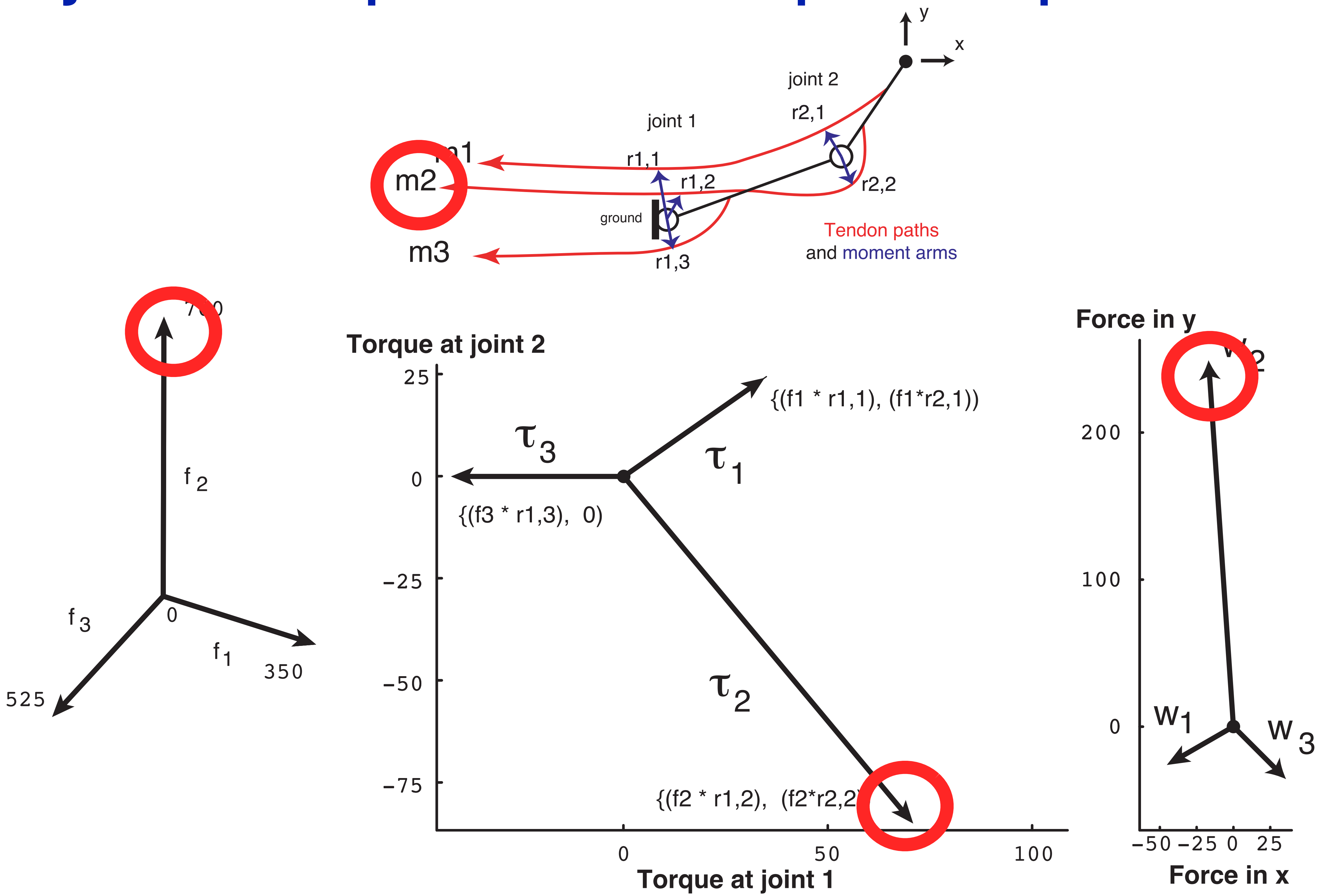

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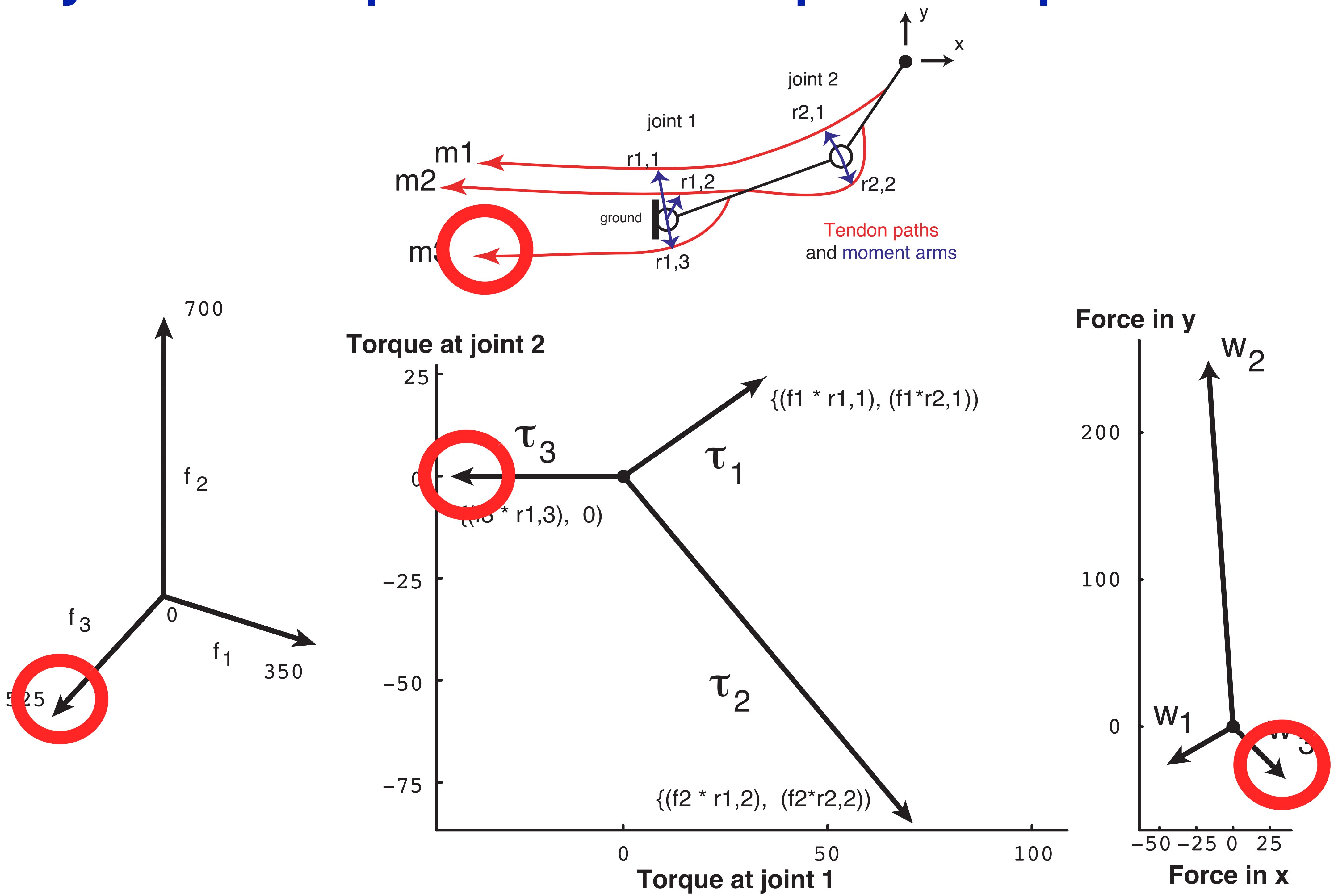

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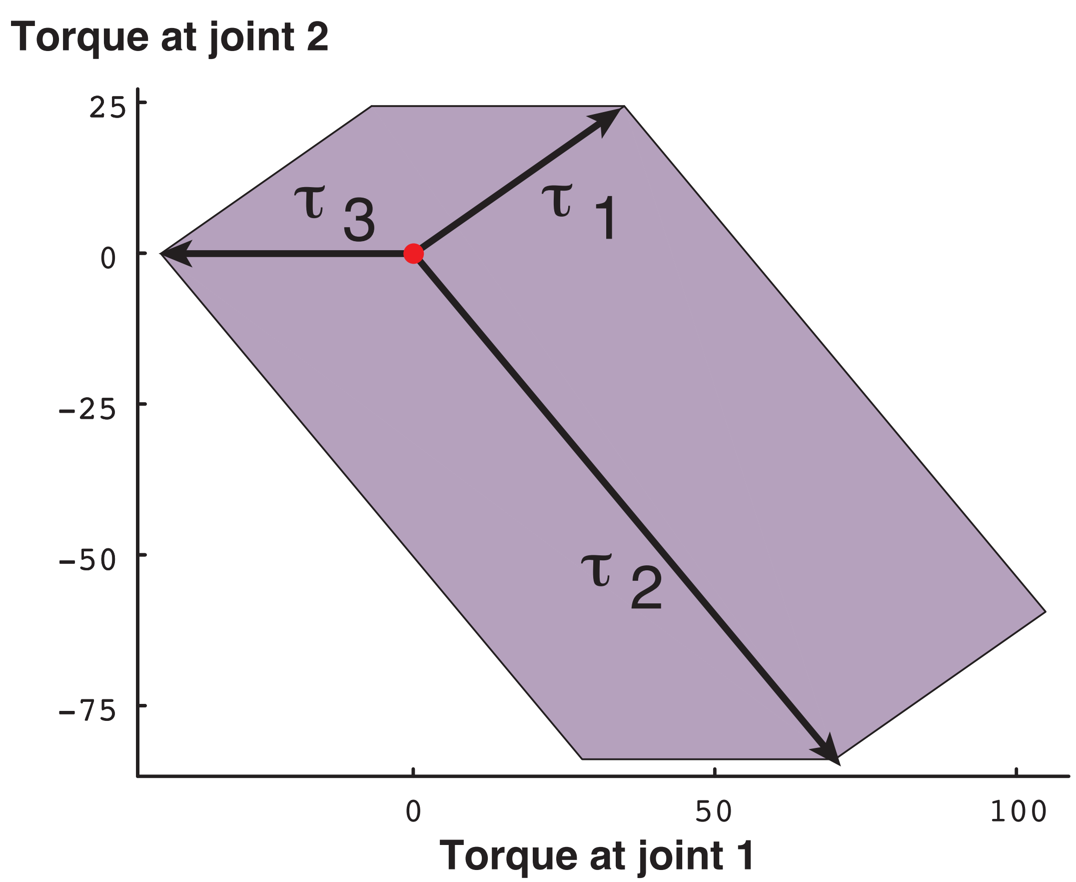
Spoor, An, Yoshikawa, Brand, Leijnse, Valero-Cuevas, etc.

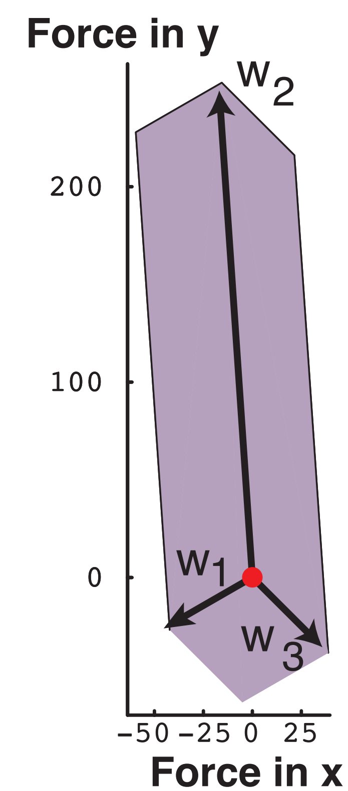
Versatility ≡ feasible torque and force sets that include the origin

convex sets remain convex under linear mapping

feasible torque set (N-m)

endpoint feasible force set (forces in N)

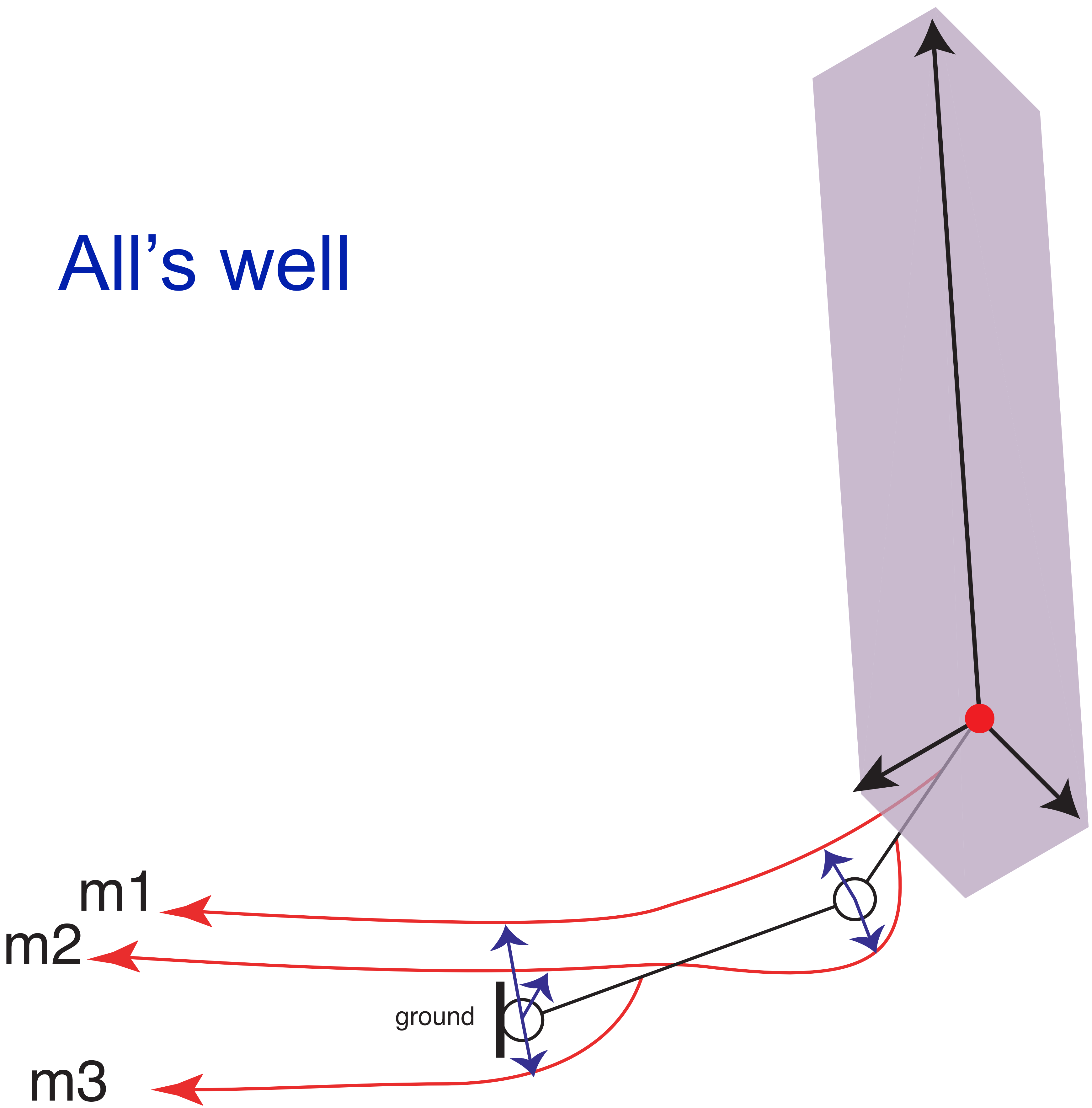




That is, producing end-point force in every Cartesian direction requires that you produce torques in every direction in “torque space”

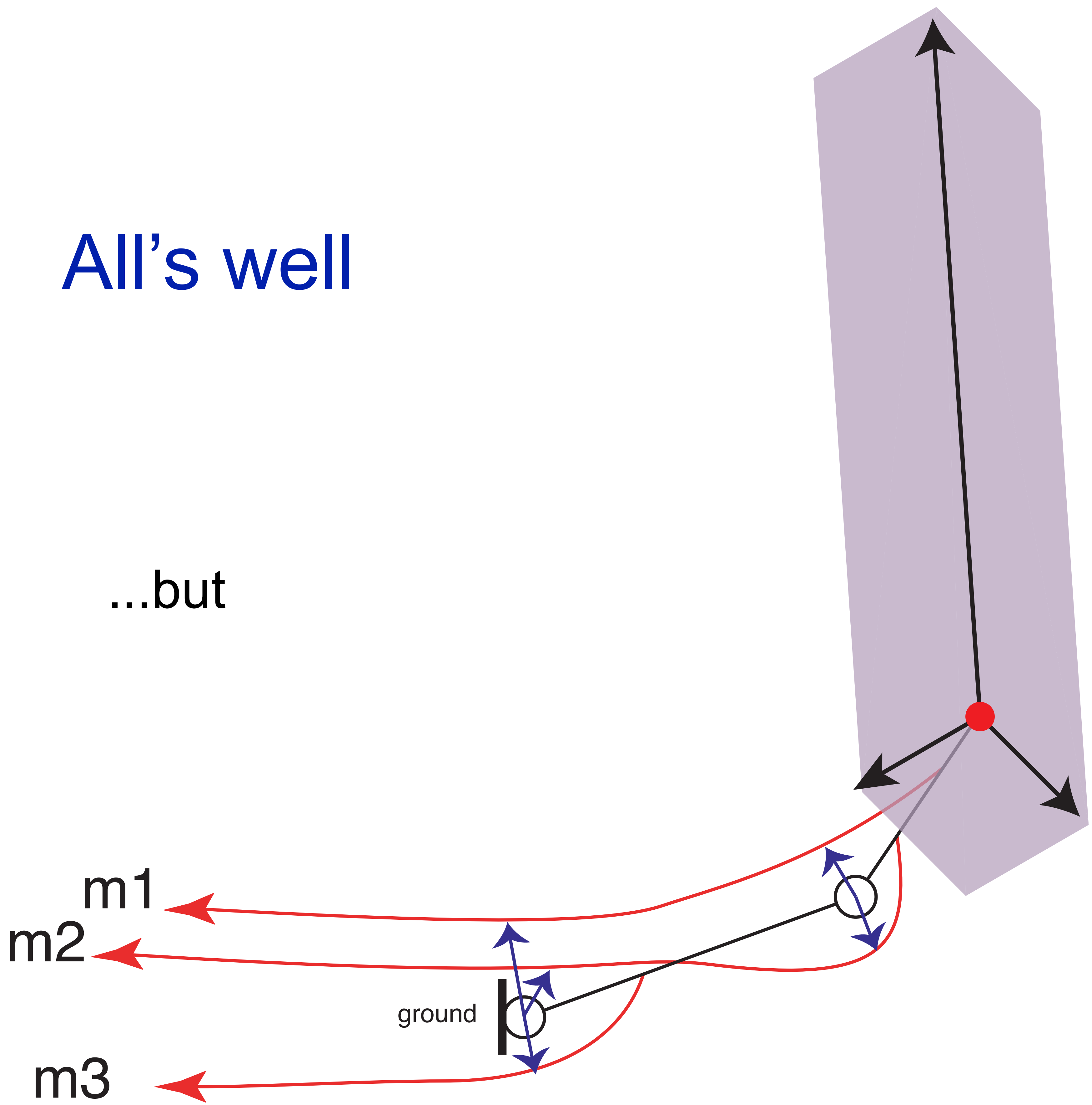
Valero-Cuevas 1998, 2005, 2009

All's well

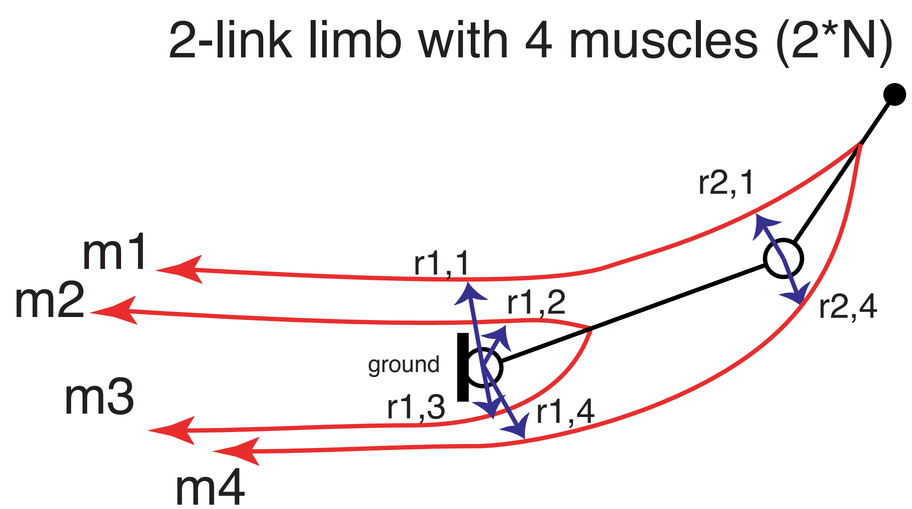


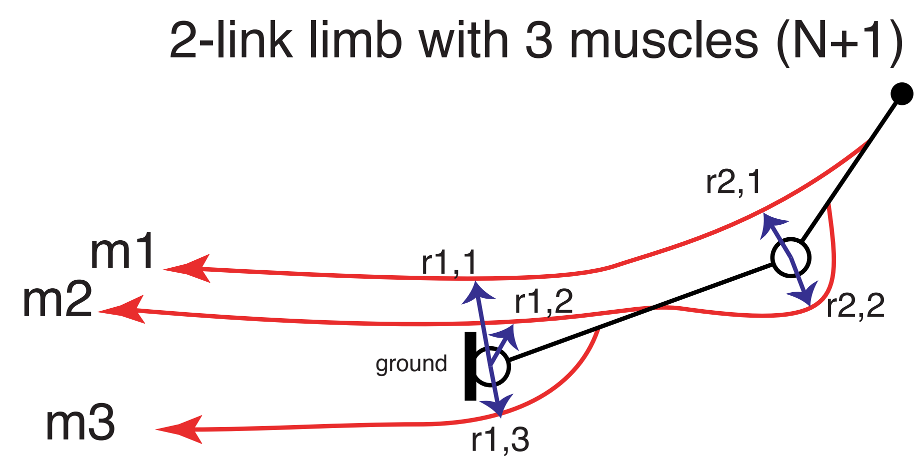
All's well

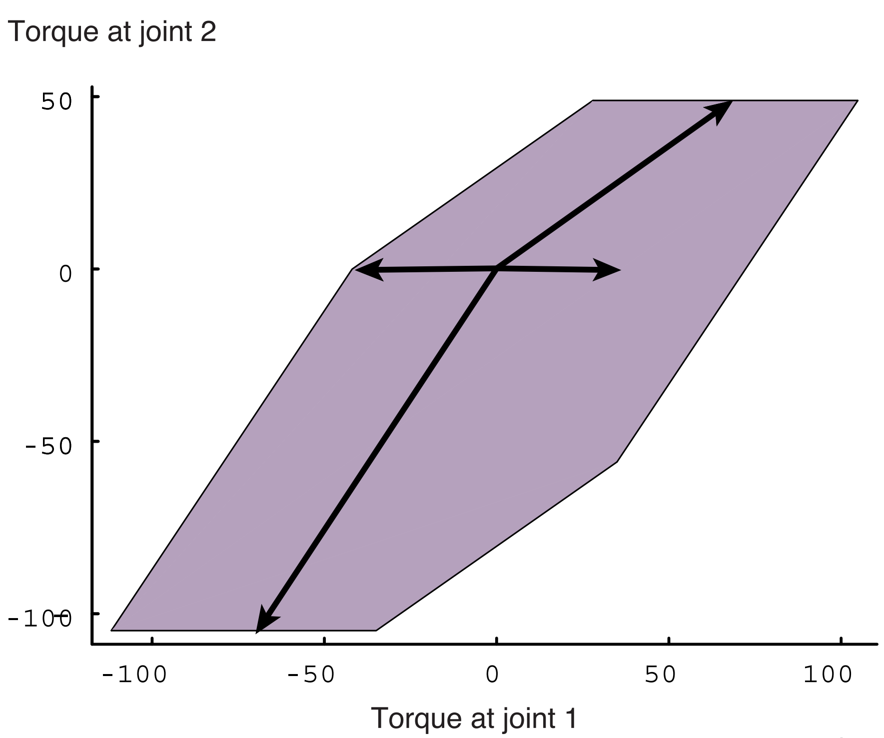
...but

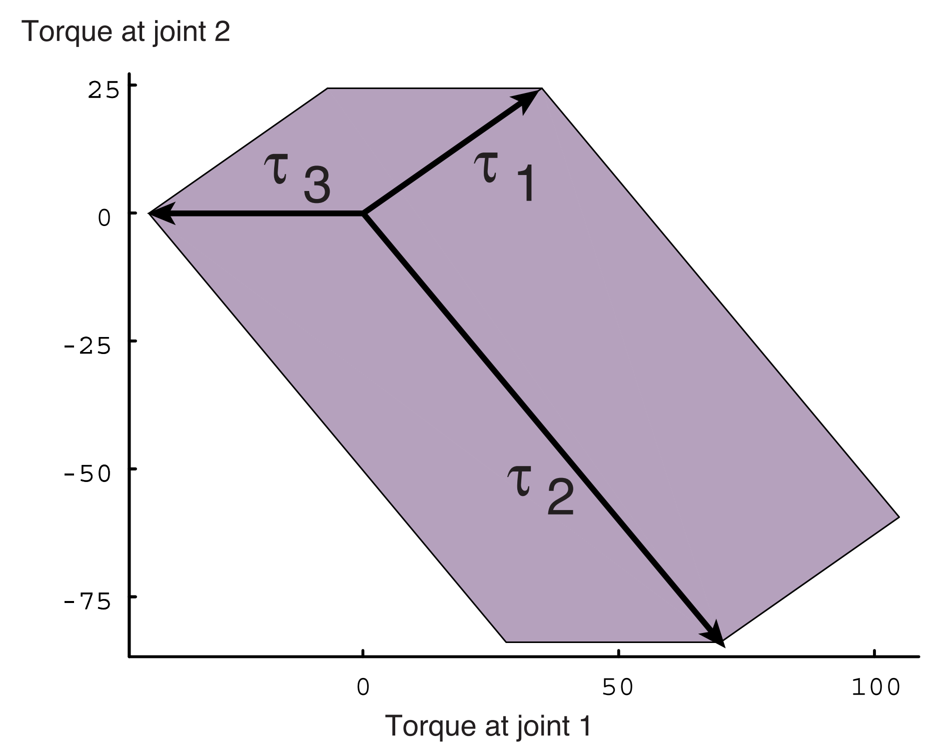


How many muscles do you need to include the origin in torque/force space?









feasible torque sets
(Newton-meters)

At least N+1 well-routed muscles

Wait a minute... but N+1 > N

Valero-Cuevas 1998, 2005, 2009

Wait a minute... but N+1 > N

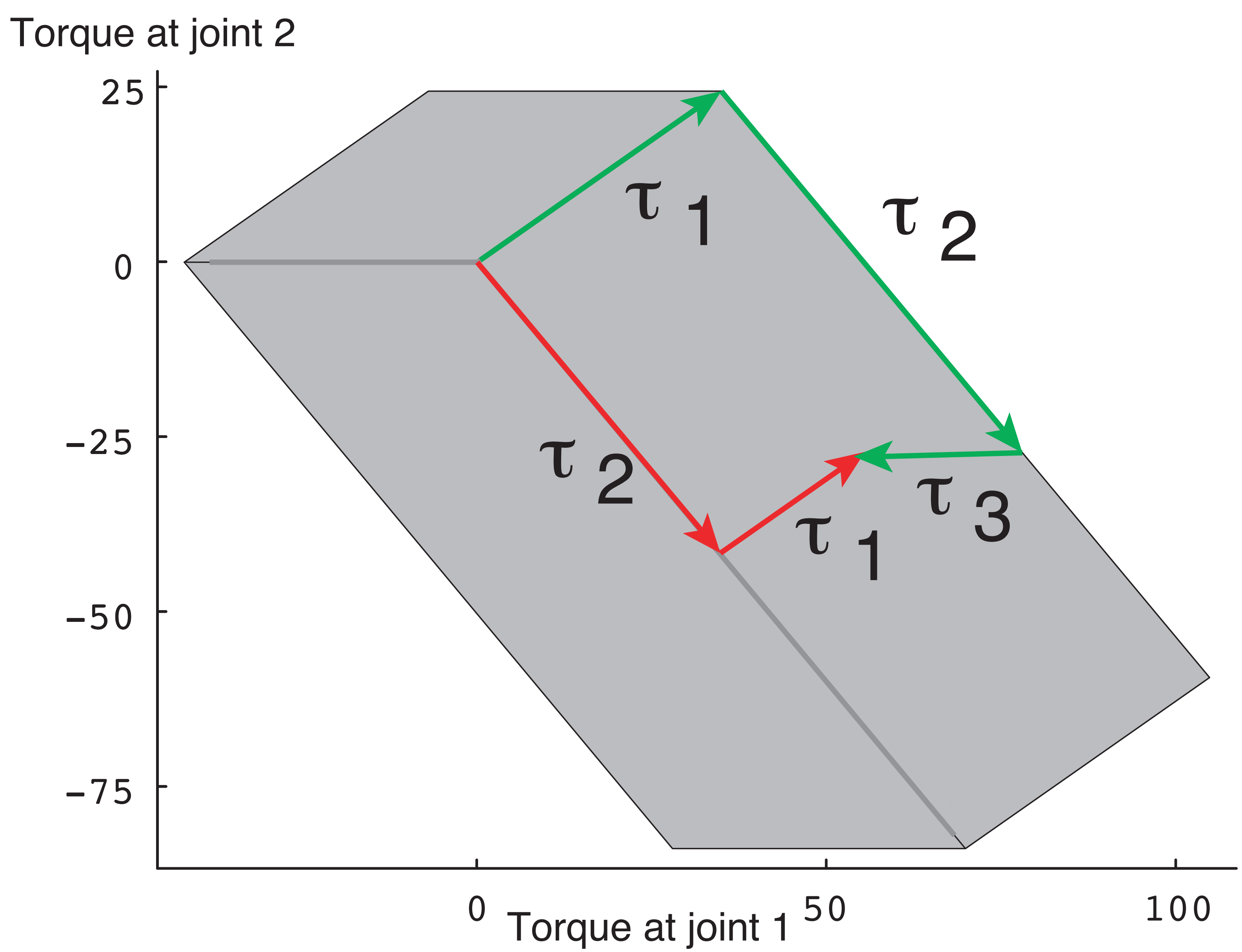
...so you need more muscles than degrees of freedom?

Valero-Cuevas 1998, 2005, 2009

Wait a minute... but N+1 > N

...so you need more muscles than degrees of freedom?

A versatile feasible torque set implies muscle redundancy for submaximal outputs!



Valero-Cuevas 1998, 2005, 2009

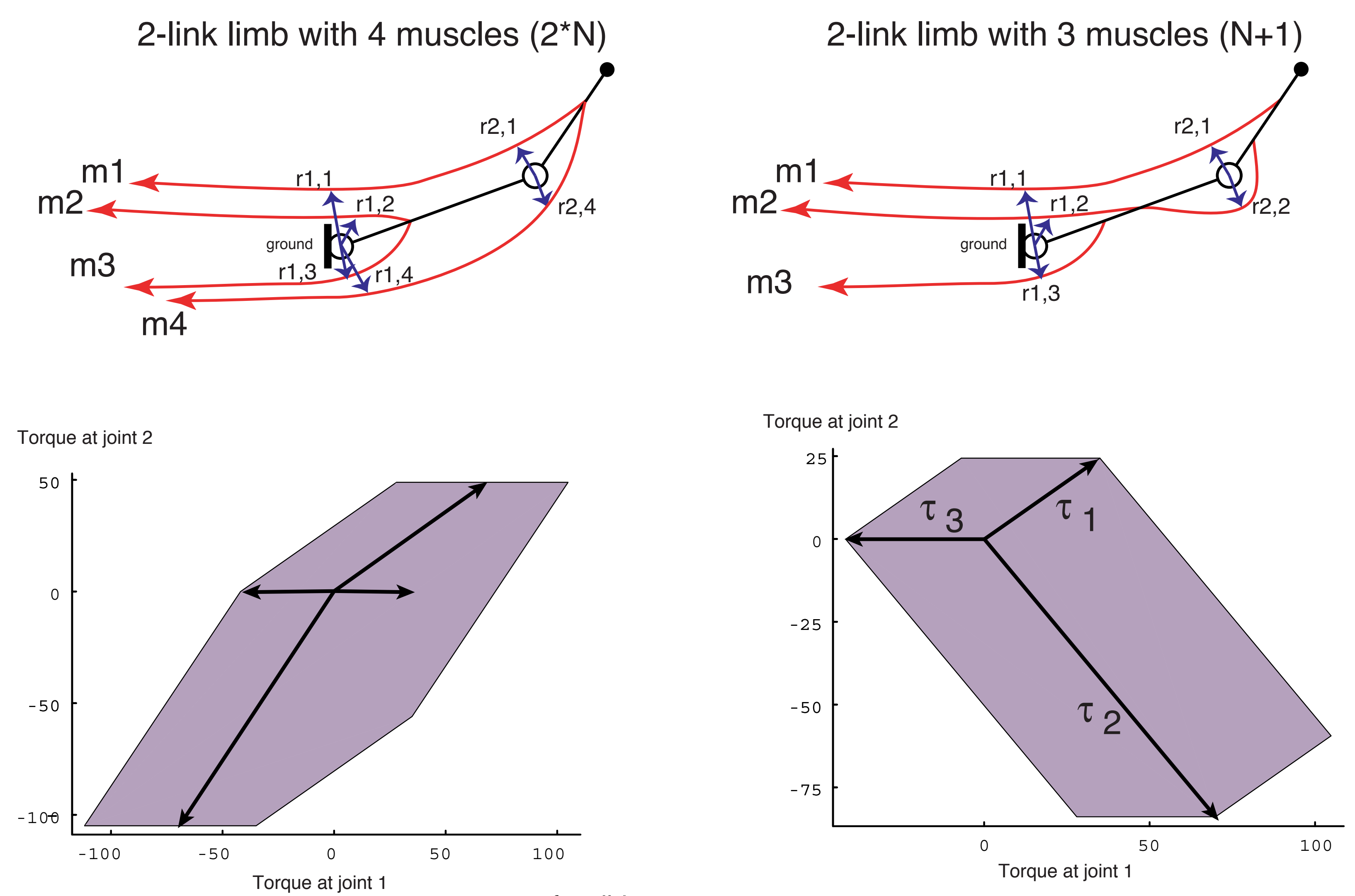
Thus, versatile tendon-driven systems require “over-actuation.”

Muscle redundancy is not an accident of evolution, but rather an appropriate structural adaptation for versatility.

The routing of the tendons also fundamentally defines the structure of the solution space.

This basis defines the size and shape of the feasible torque and feasible force sets

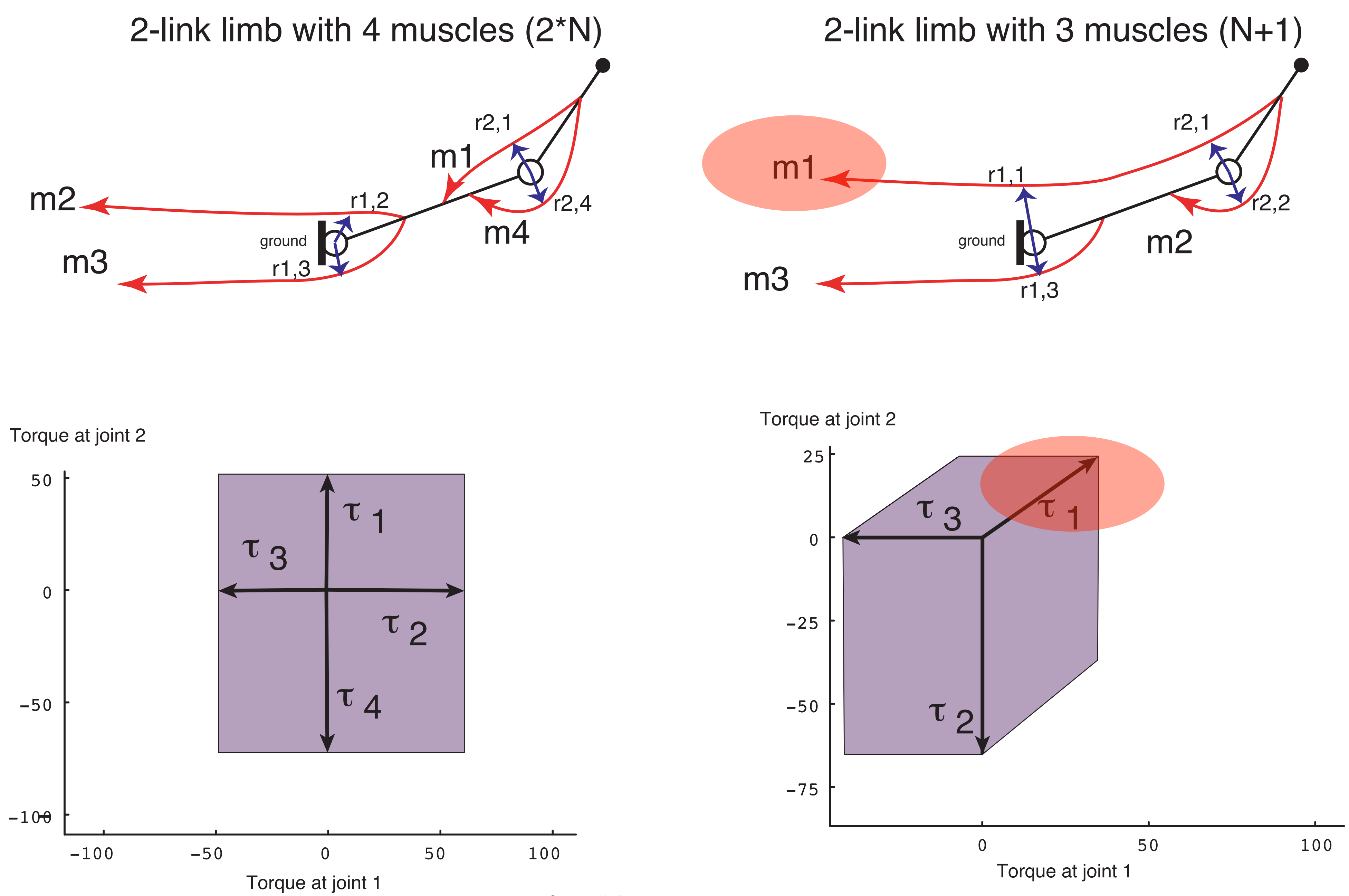
This leads to preferential gains and directions of action at the output.



feasible torque sets
(Newton-meters)

Valero-Cuevas 1998, 2005, 2009

You did say >N+1 “well-routed,” right?



feasible torque sets
(Newton-meters)

Multi-articular muscles simply have diagonal actions in torque space

Valero-Cuevas. A mathematical approach to the mechanical capabilities of limbs and fingers. PMC V 2009.

Consequences for control

Redundancy does not imply robustness

Journal of Biomechanics ■ (■■■■) ■■■–■■■

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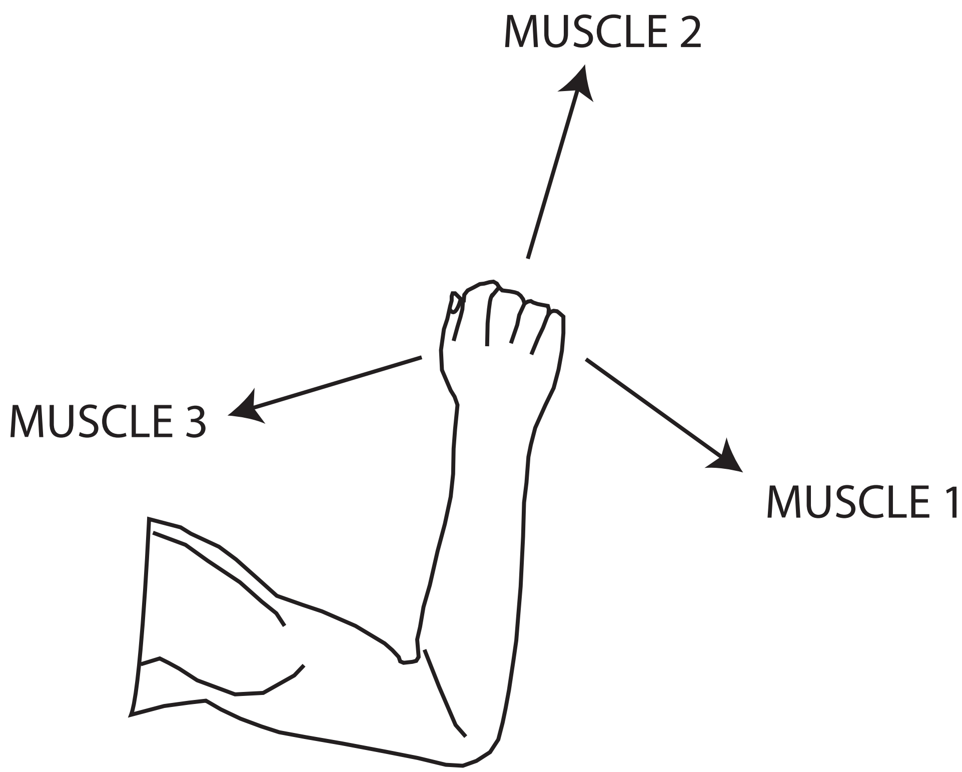
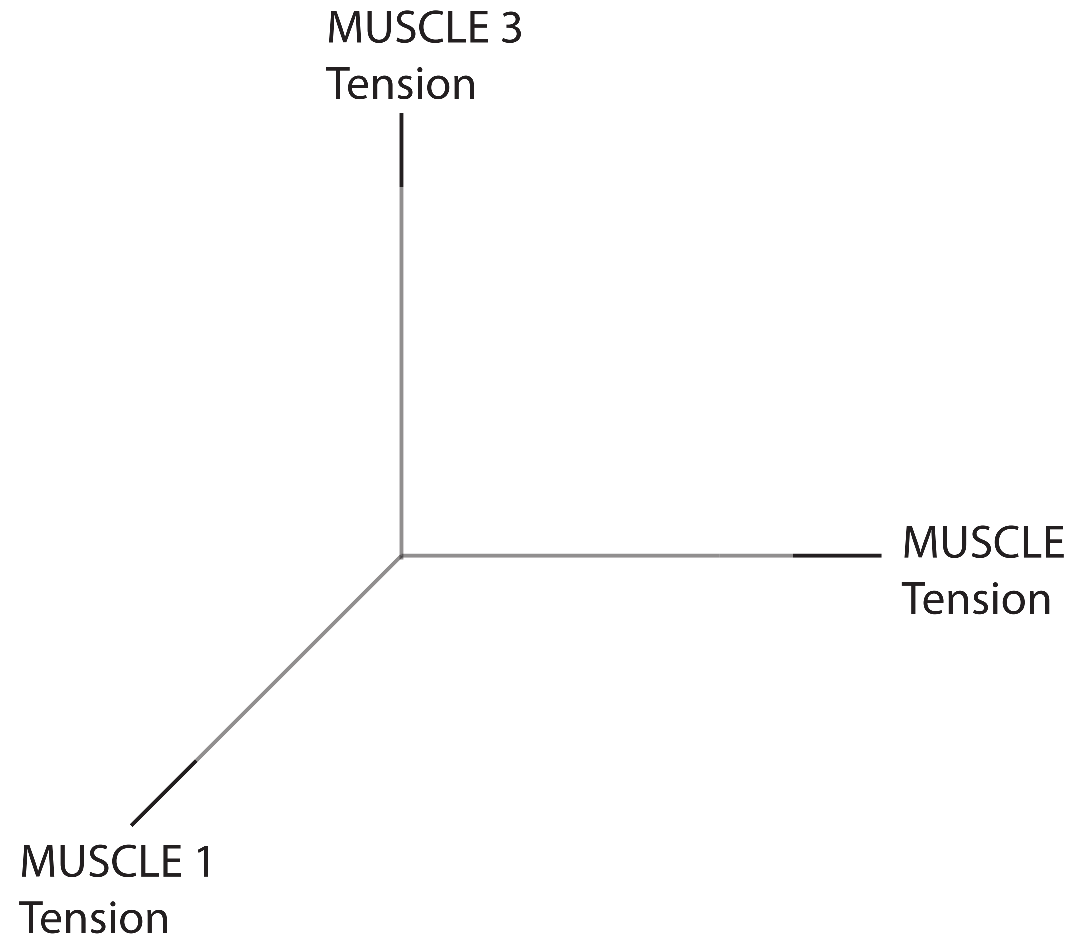
Muscle redundancy does not imply robustness to muscle dysfunction

Jason J. Kutch [a], Francisco J. Valero-Cuevas [a,b,*]

[a] Department of Biomedical Engineering, University of Southern California, Los Angeles, CA, USA
[b] Division of Biokinesiology & Physical Therapy, University of Southern California, Los Angeles, CA, USA

Solution space for a particular output





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Kutch & Valero-Cuevas, J Biomech 2011

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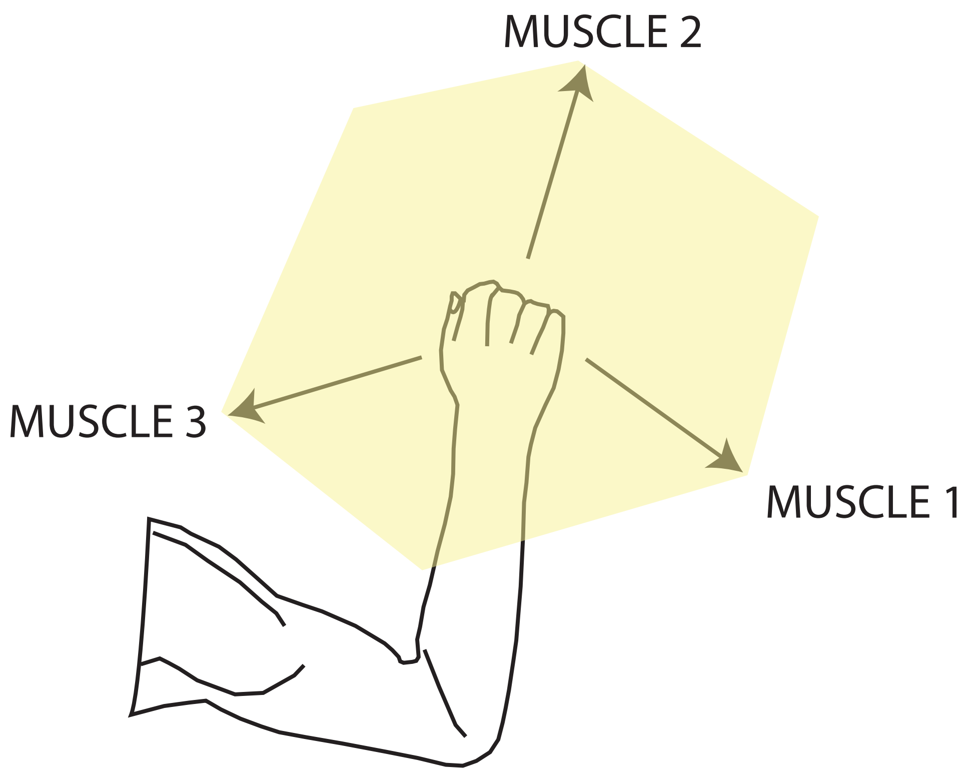

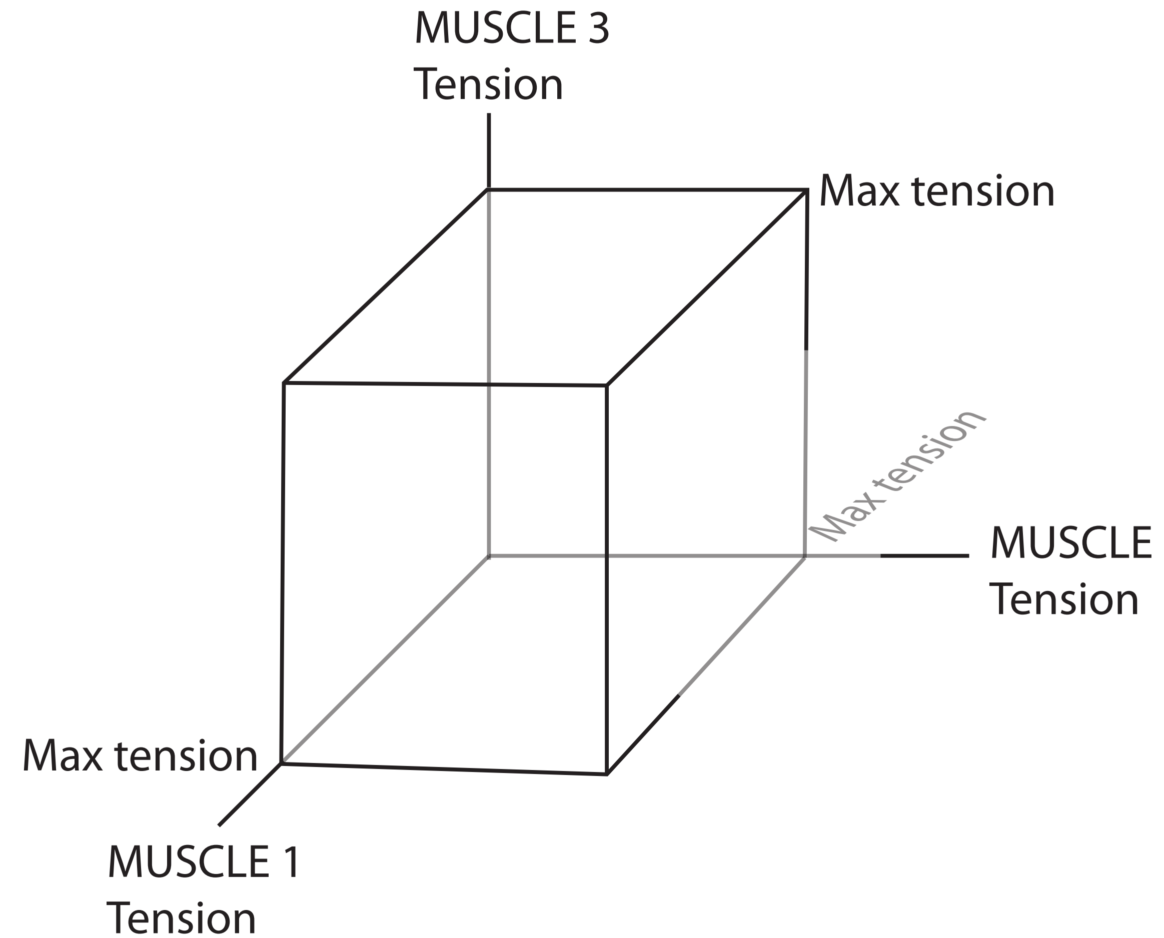

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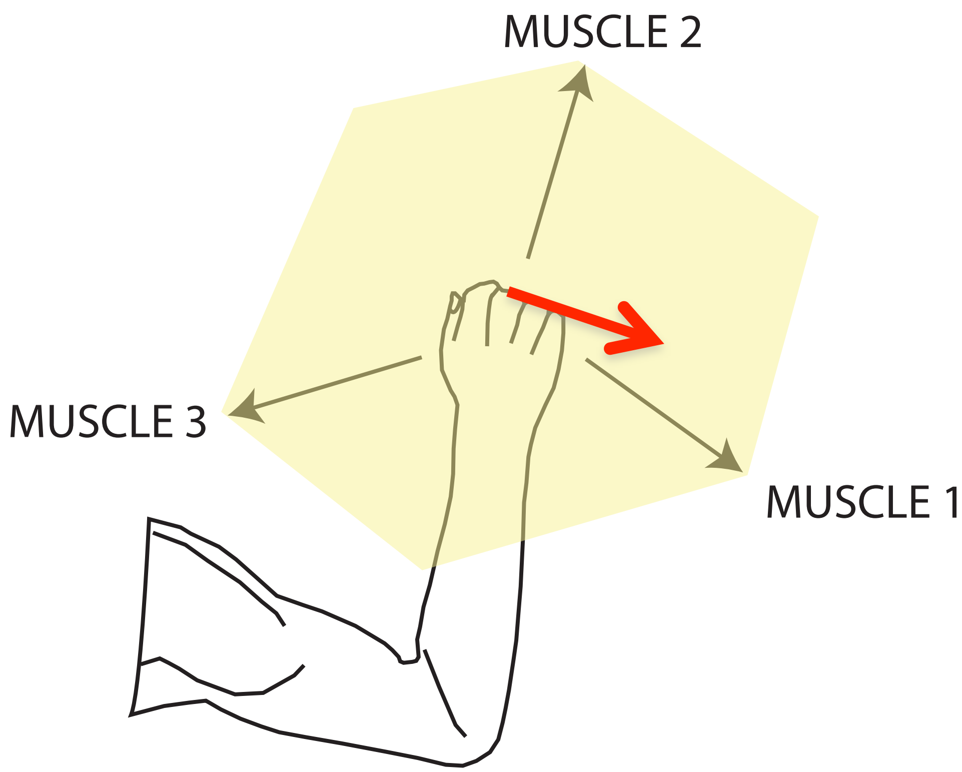

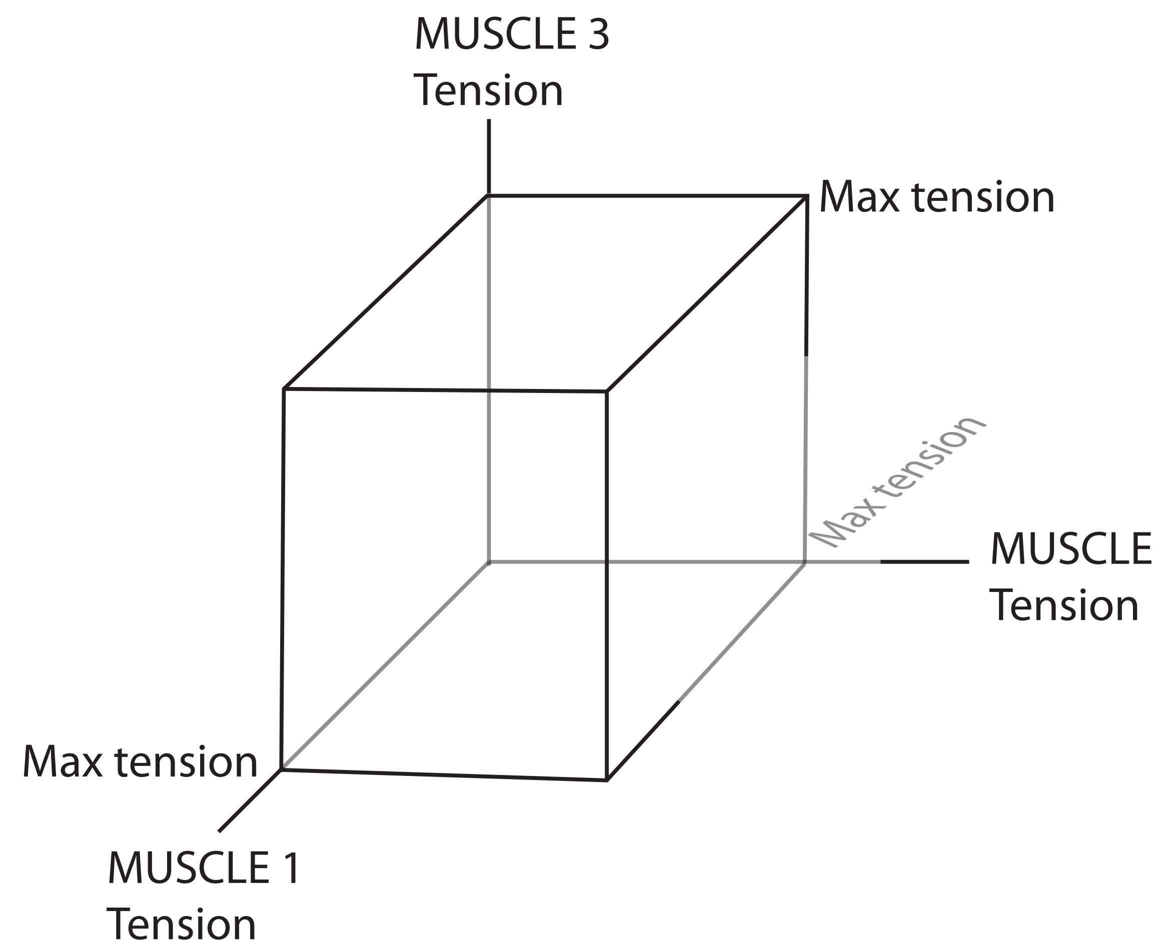

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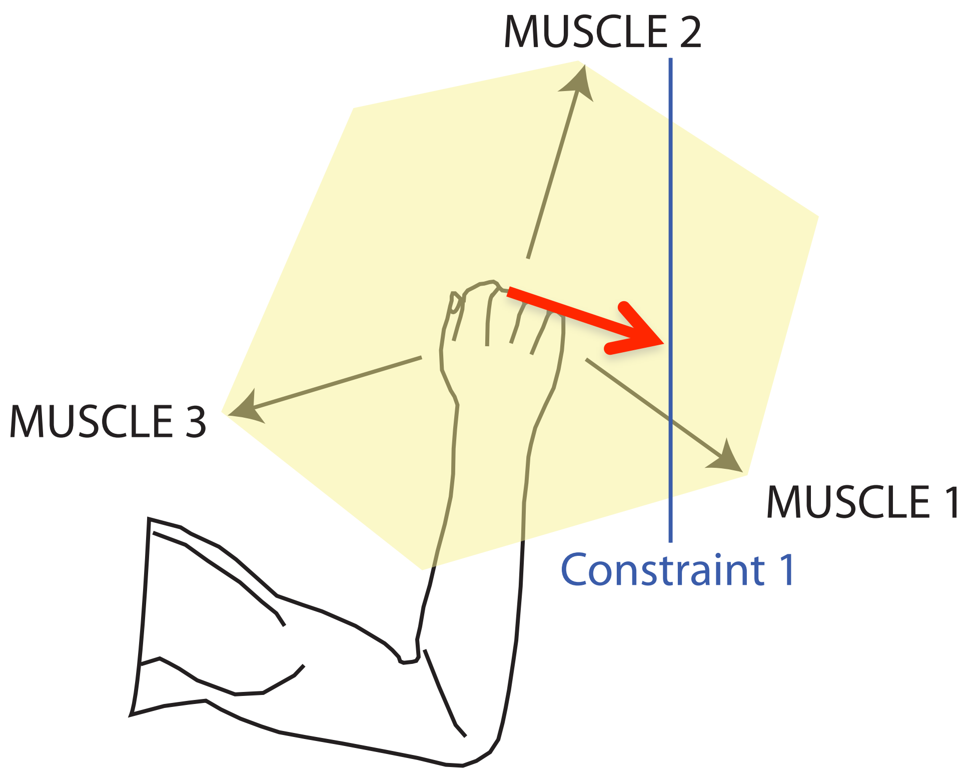

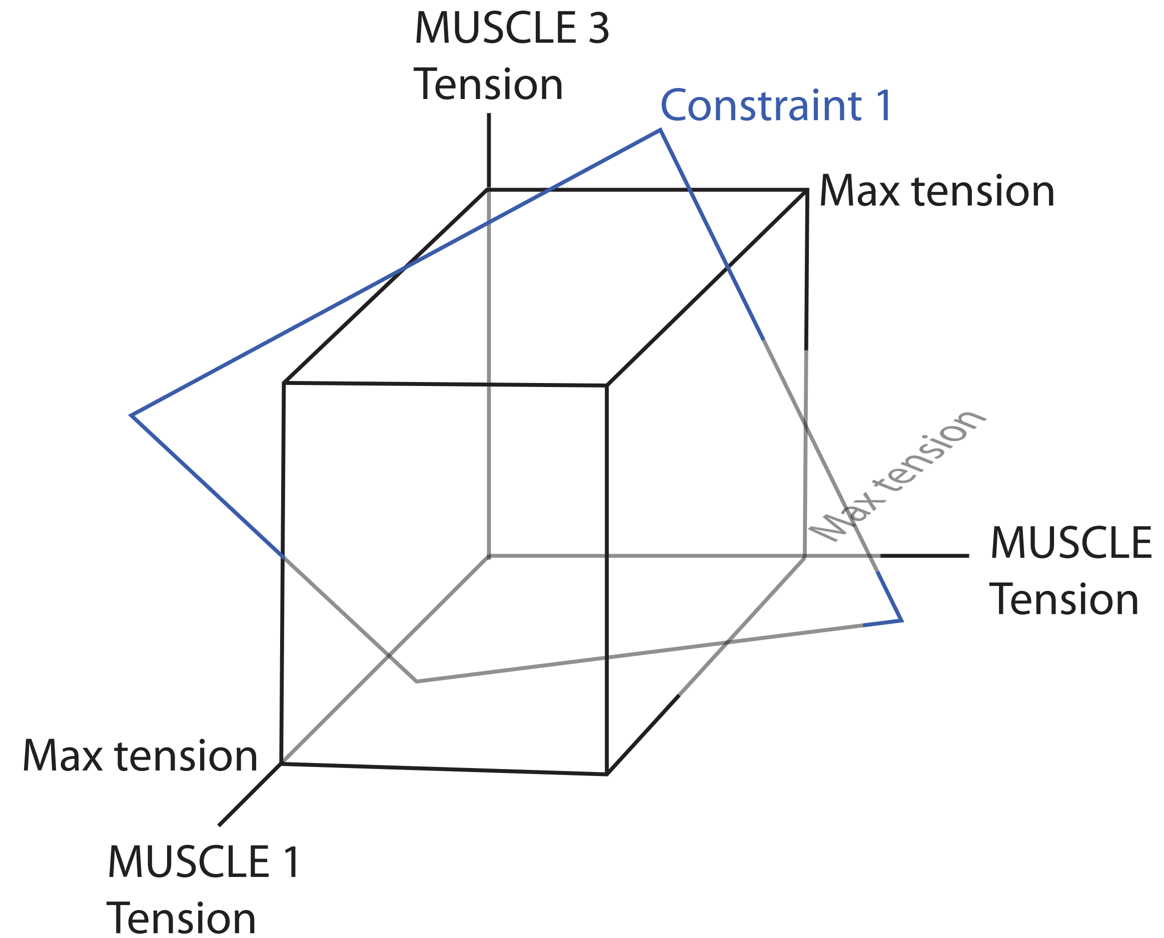

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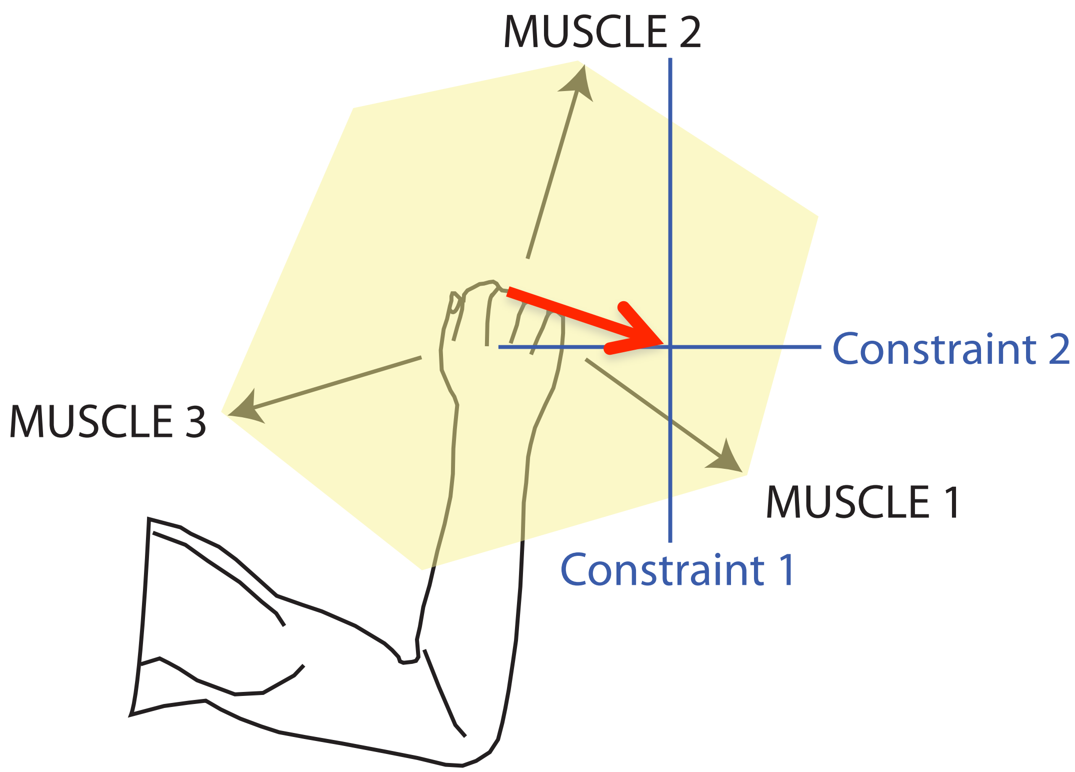

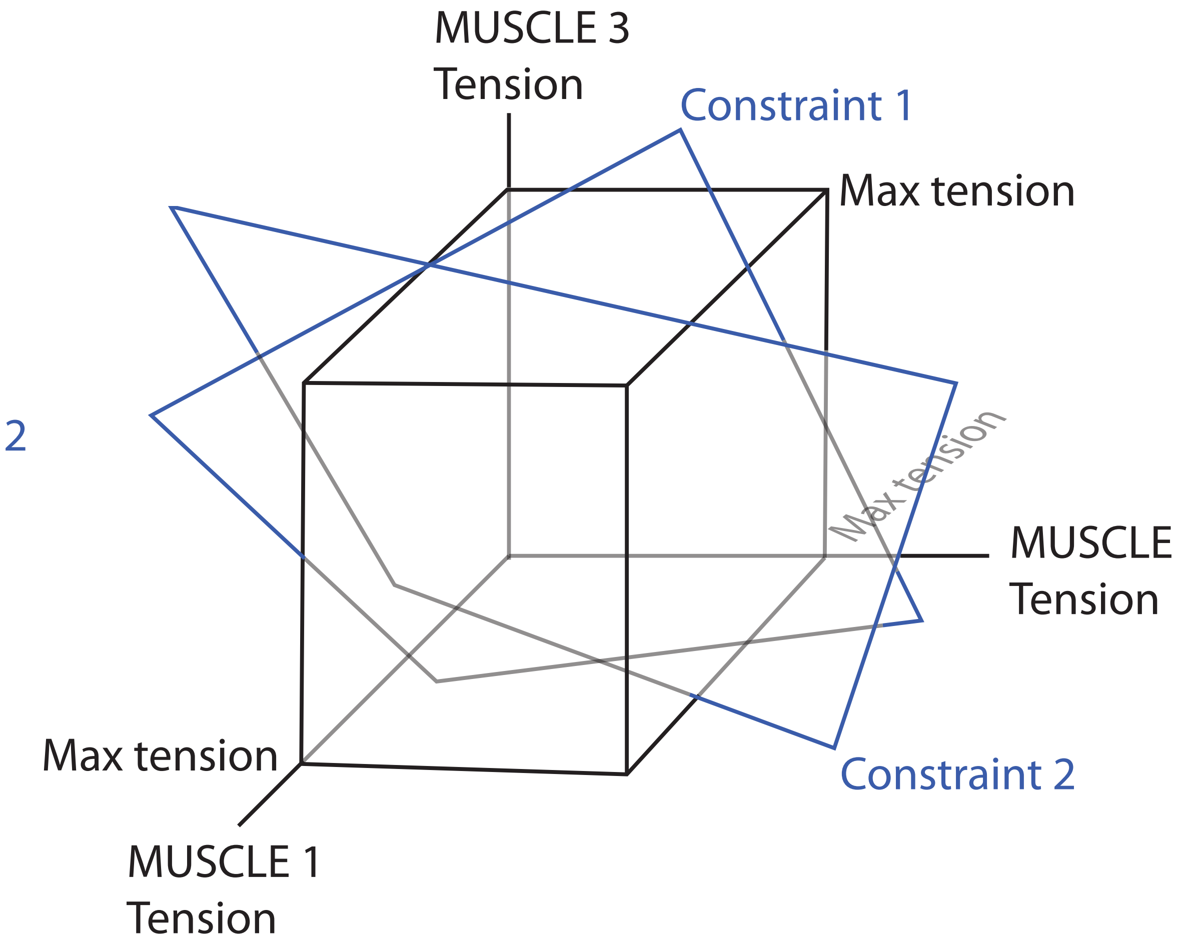

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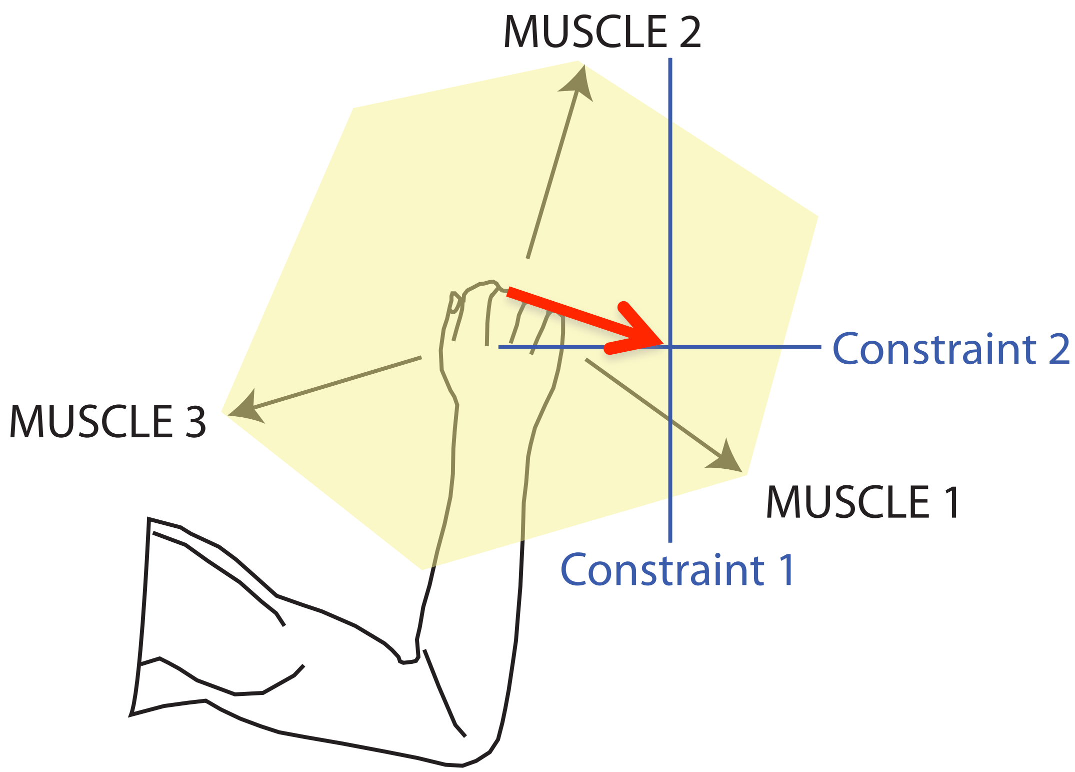

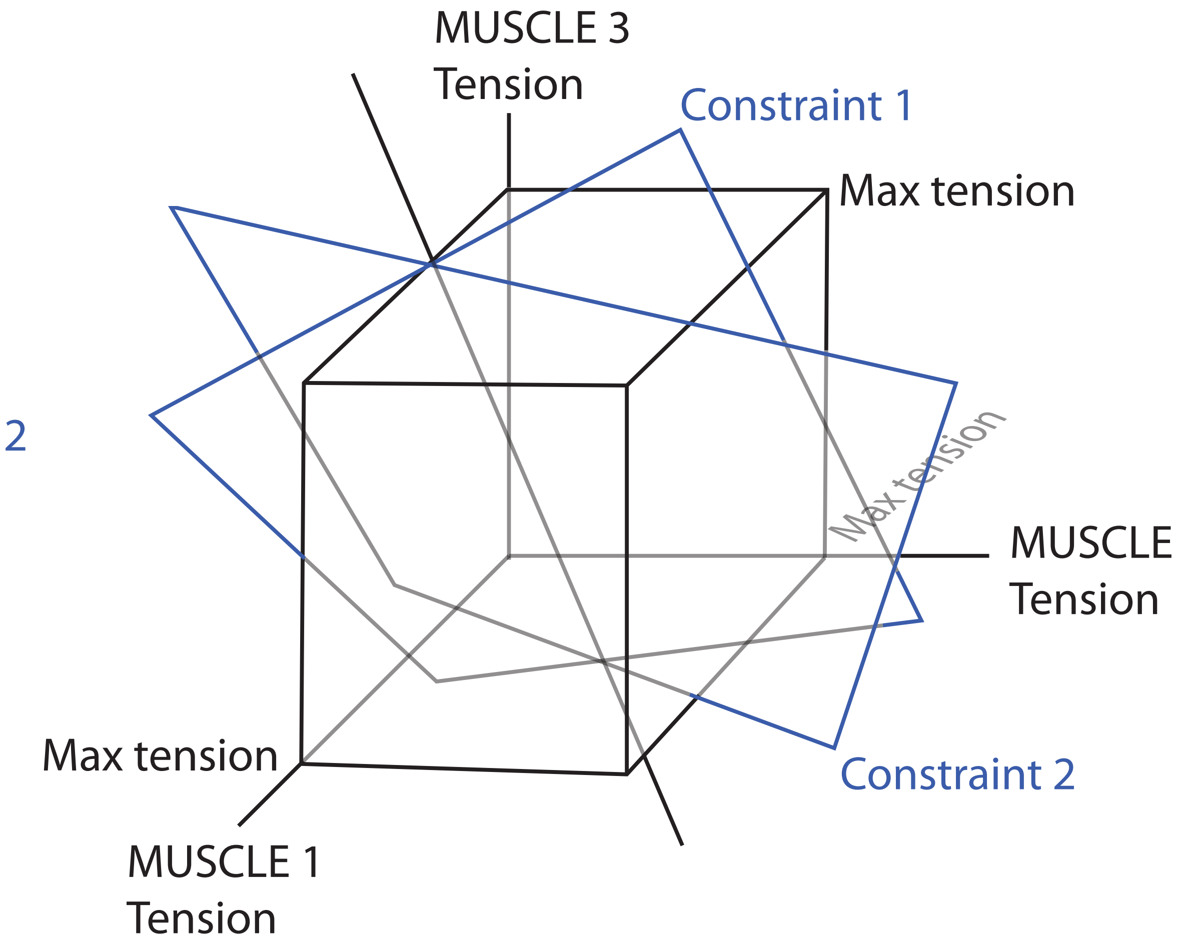

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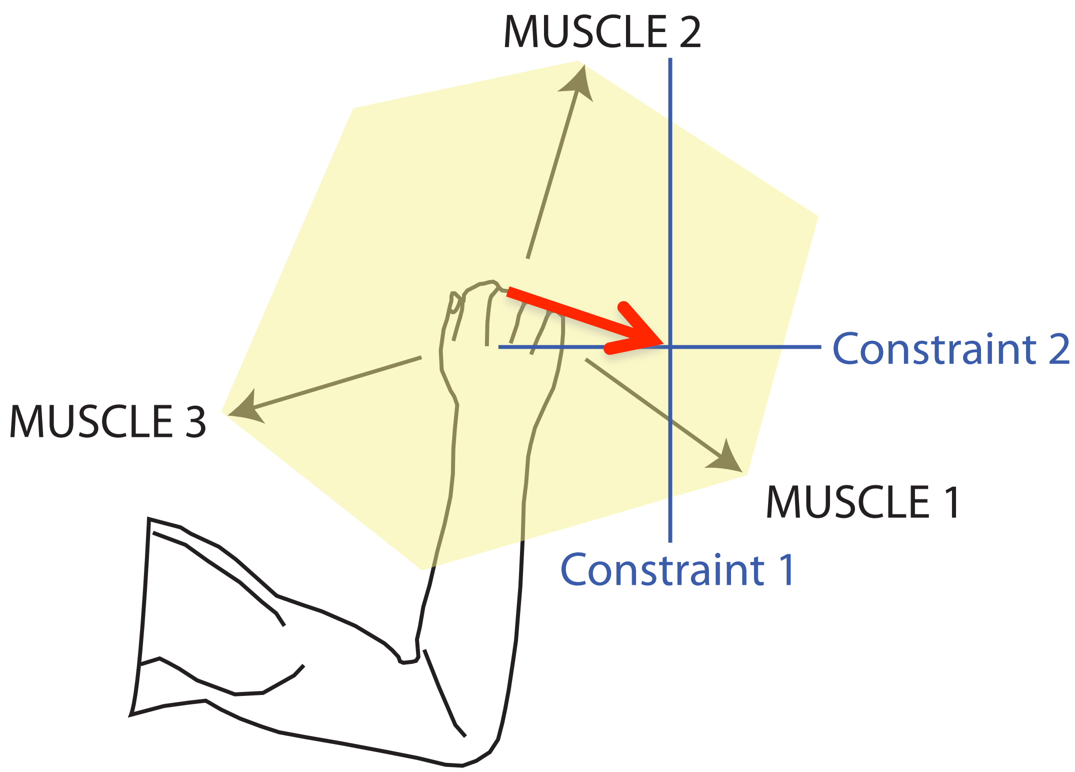

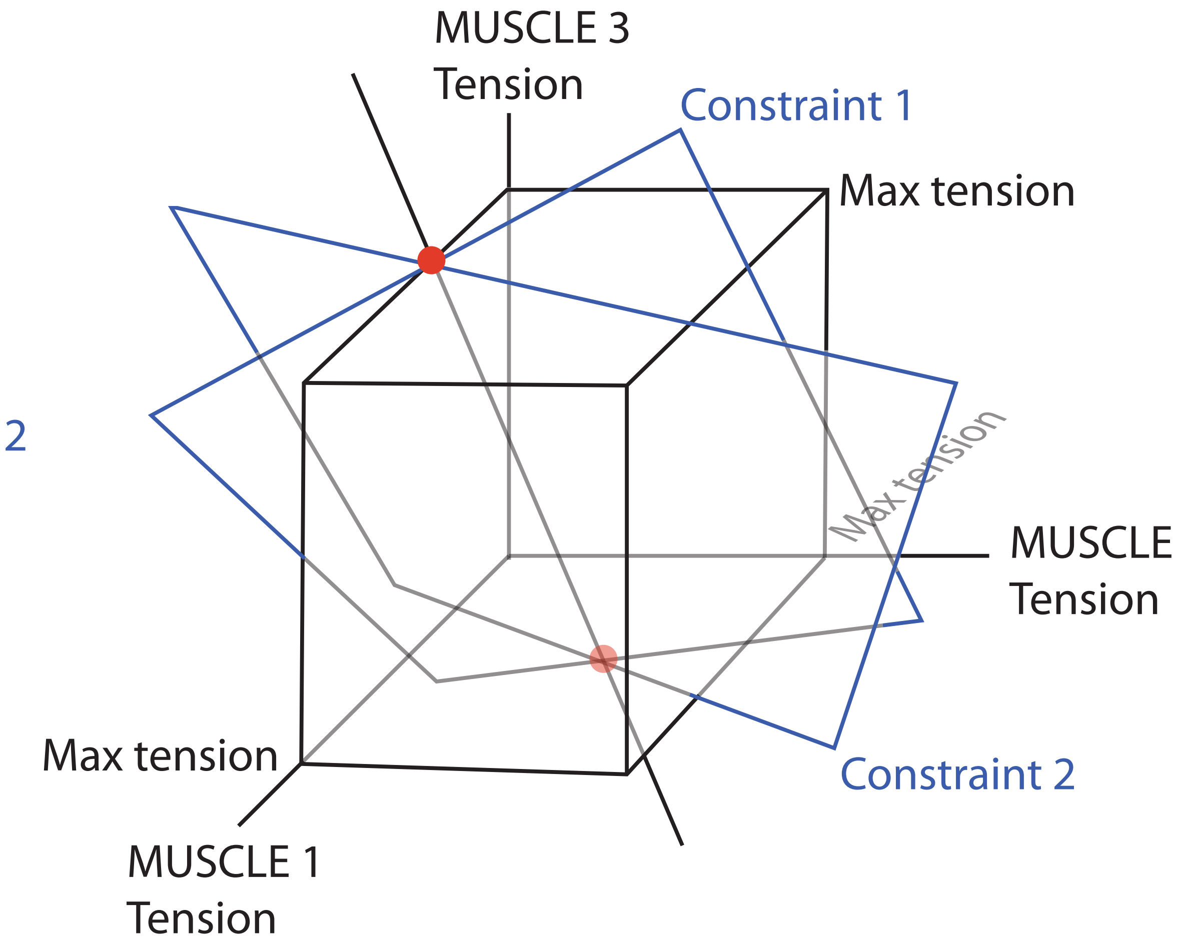

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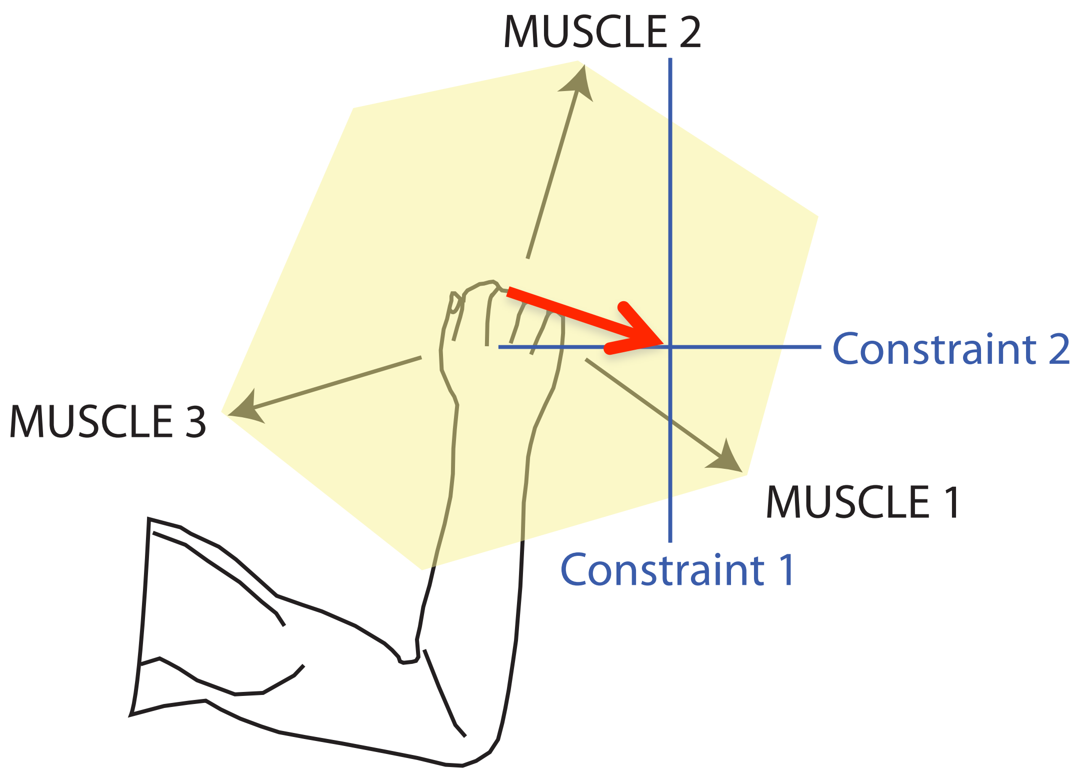

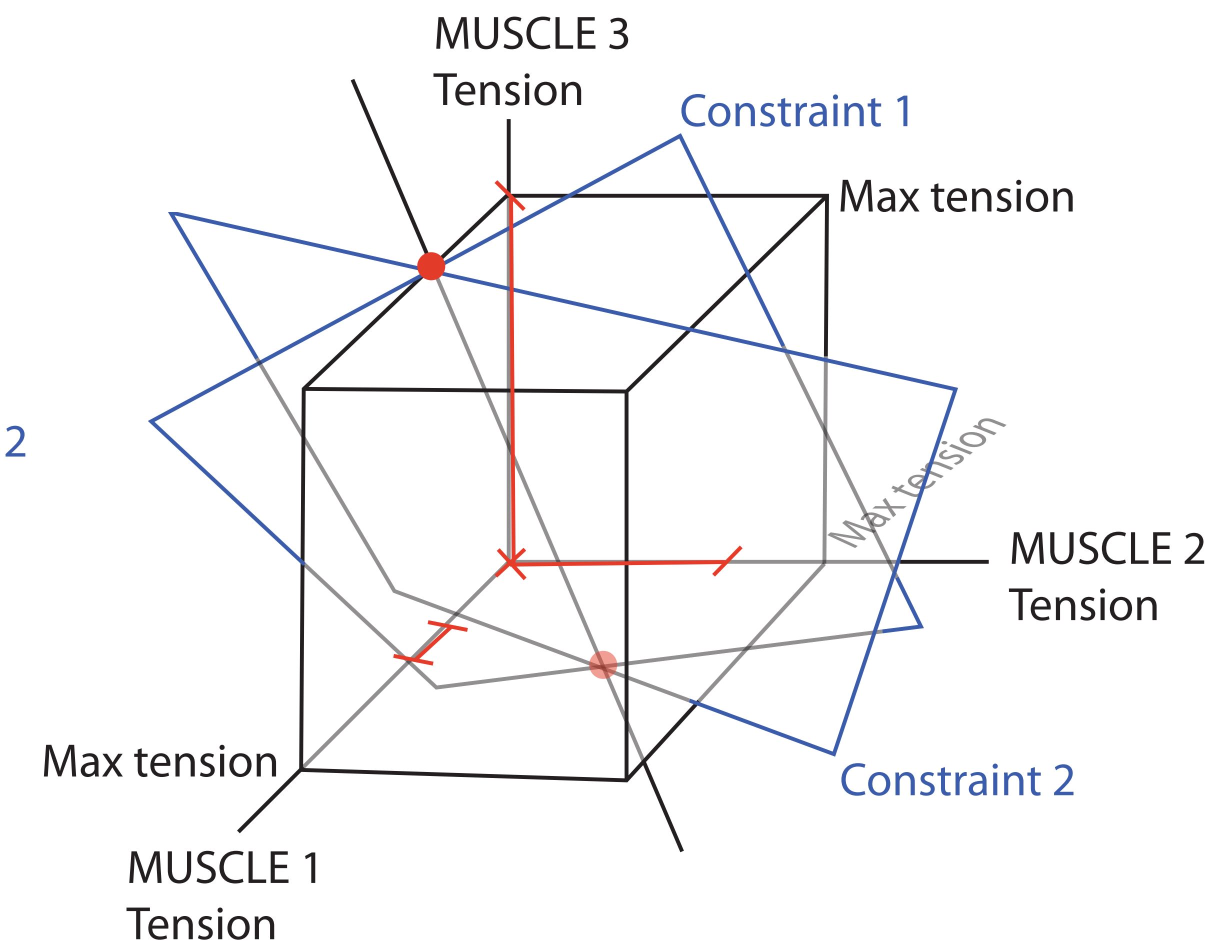

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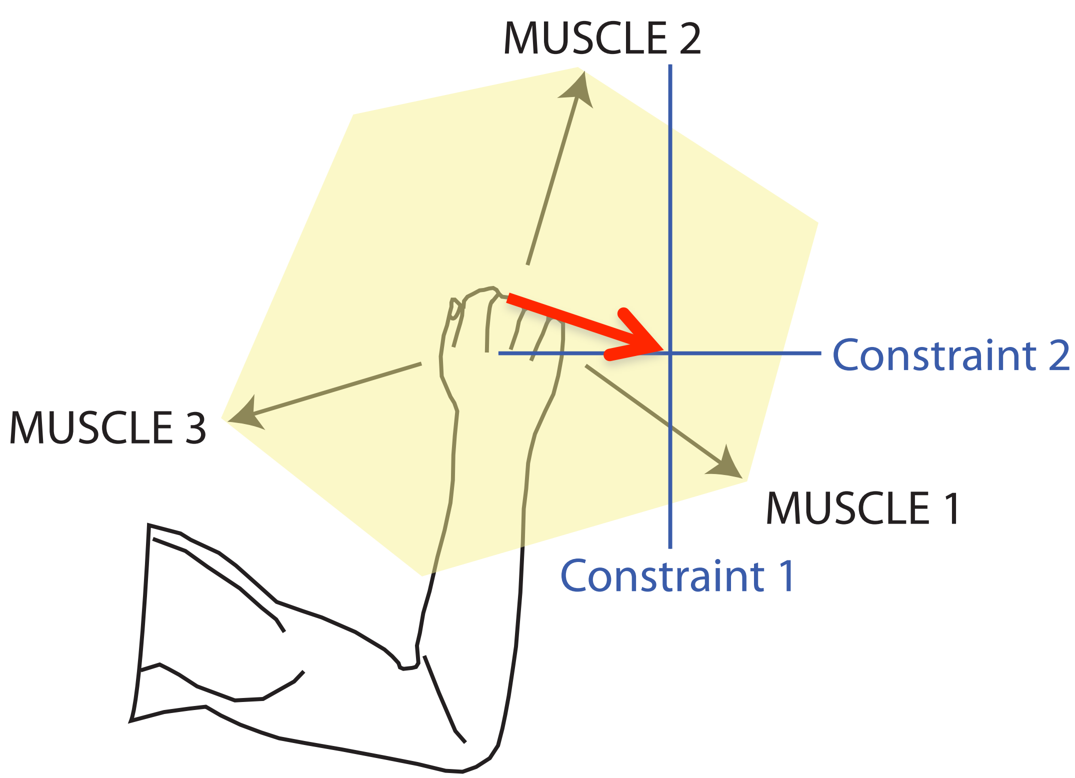

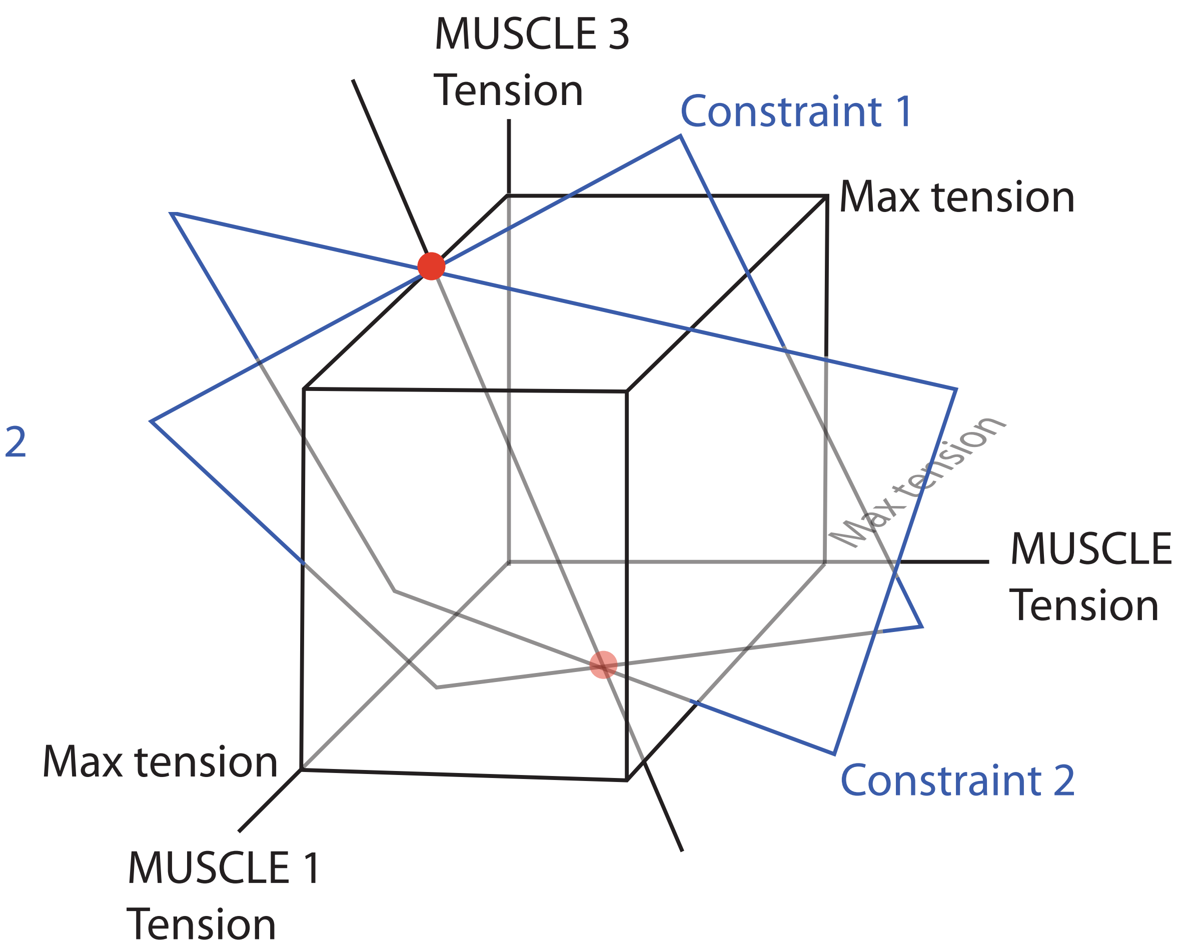

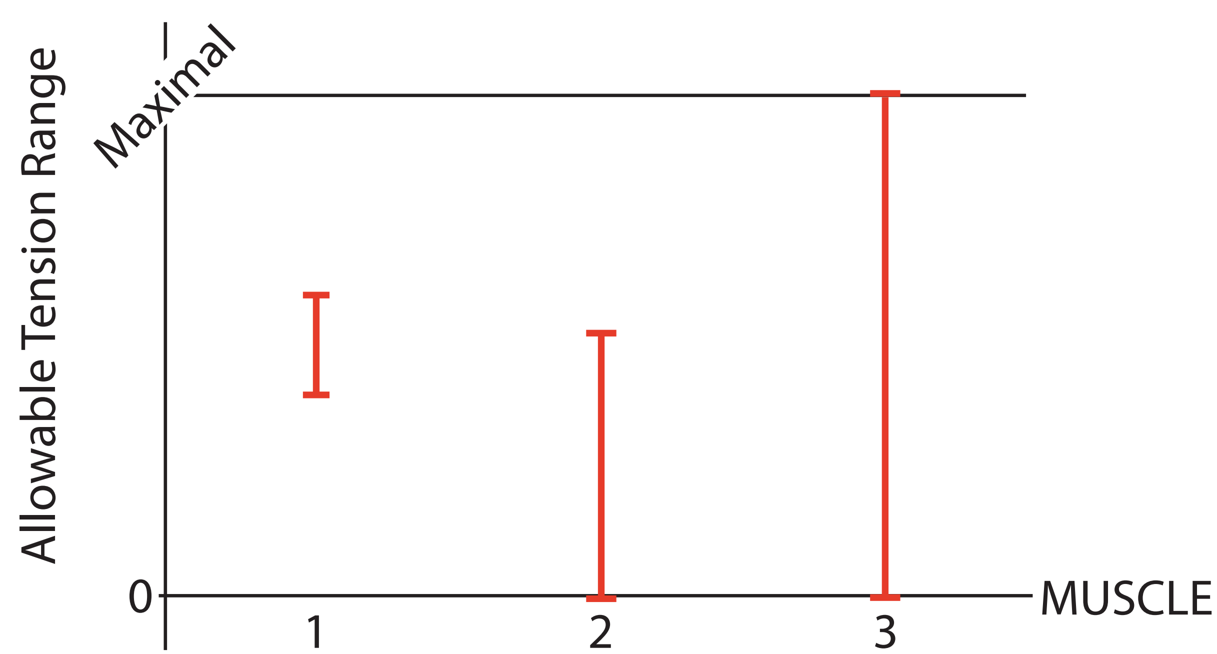

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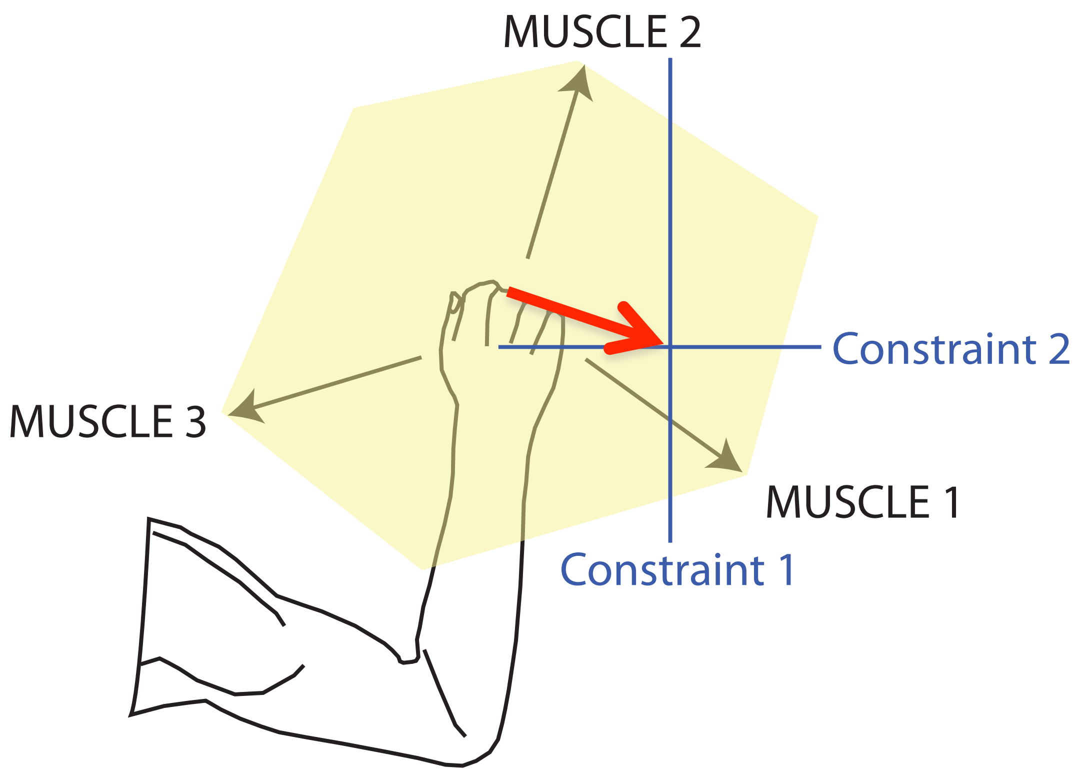

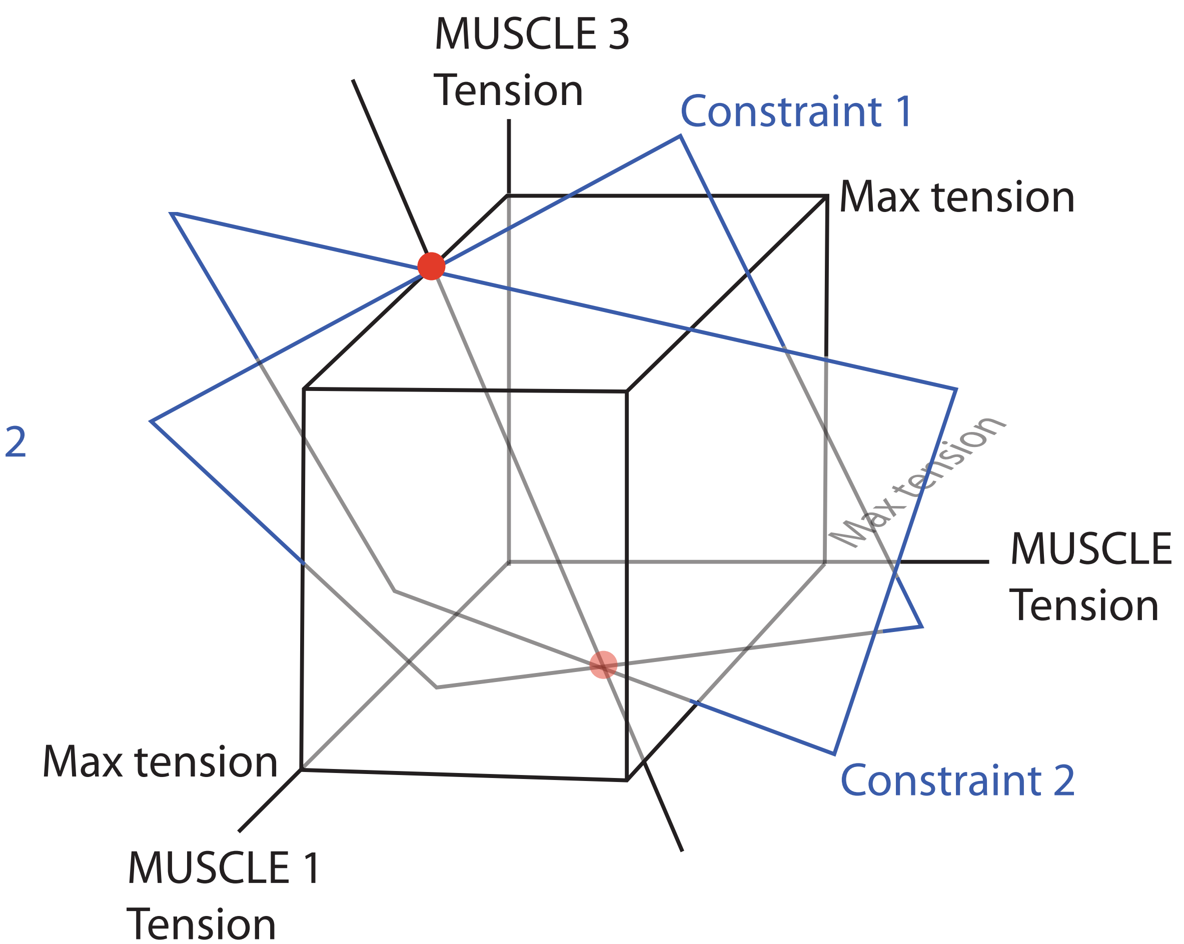

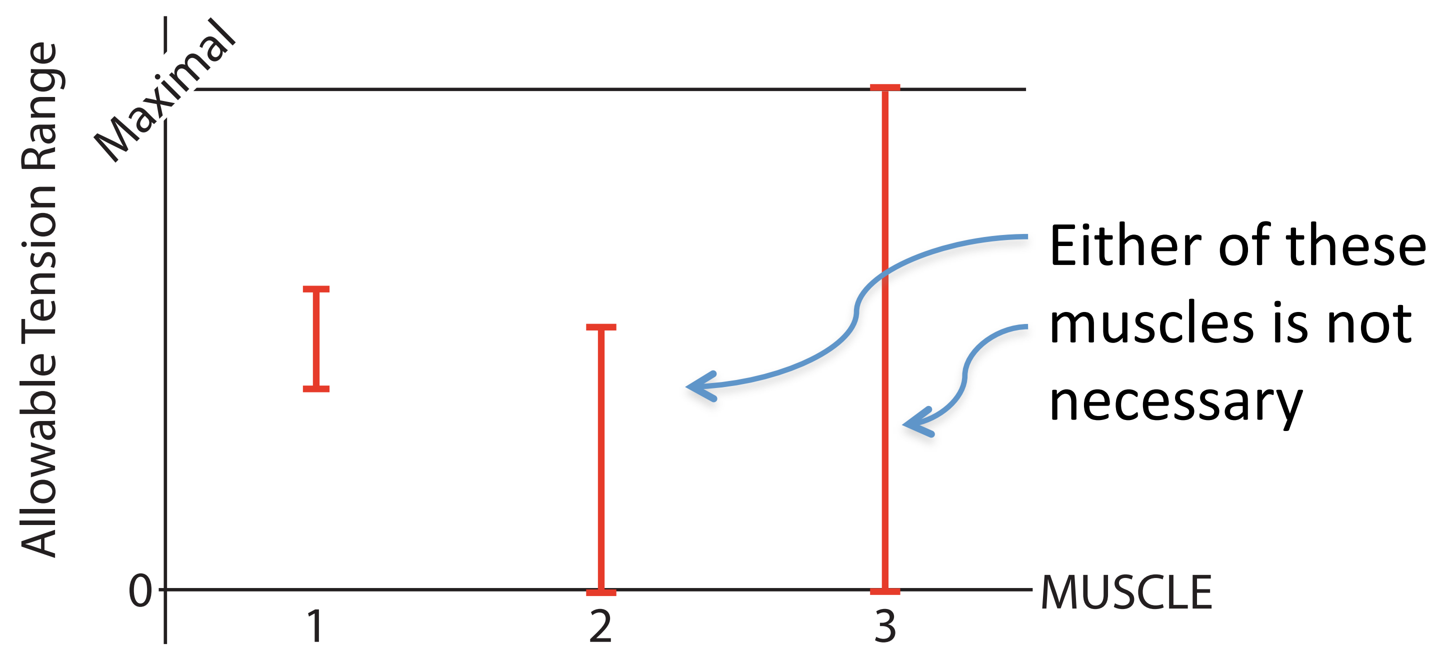

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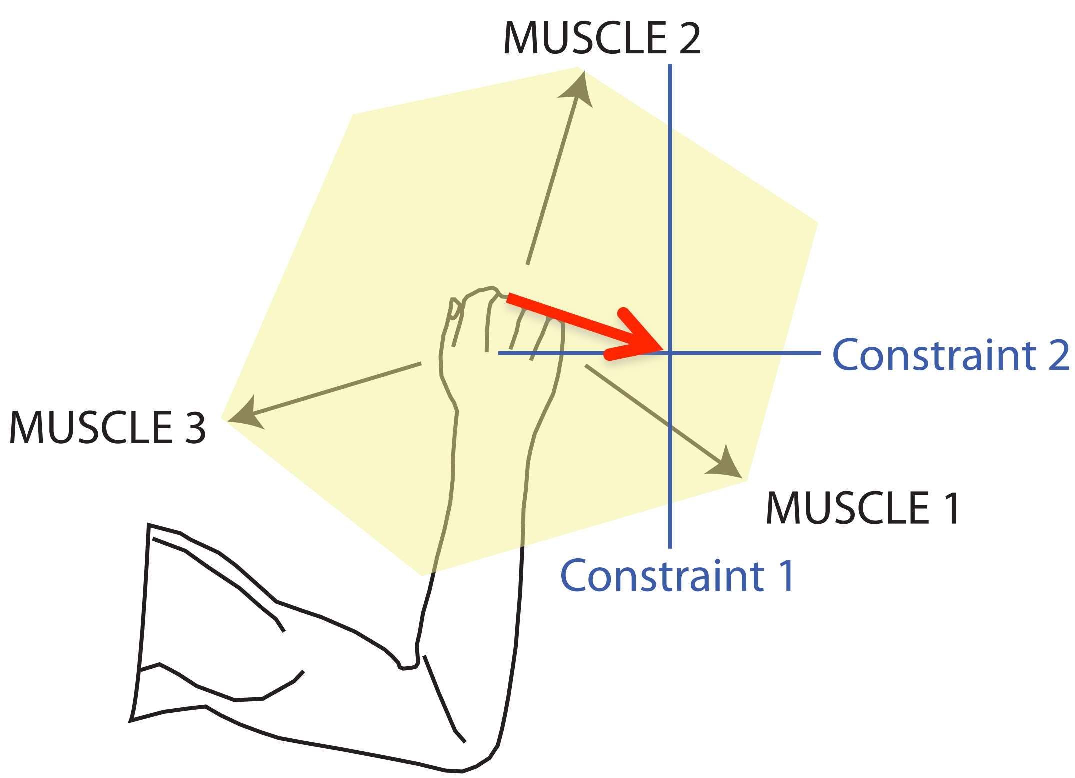

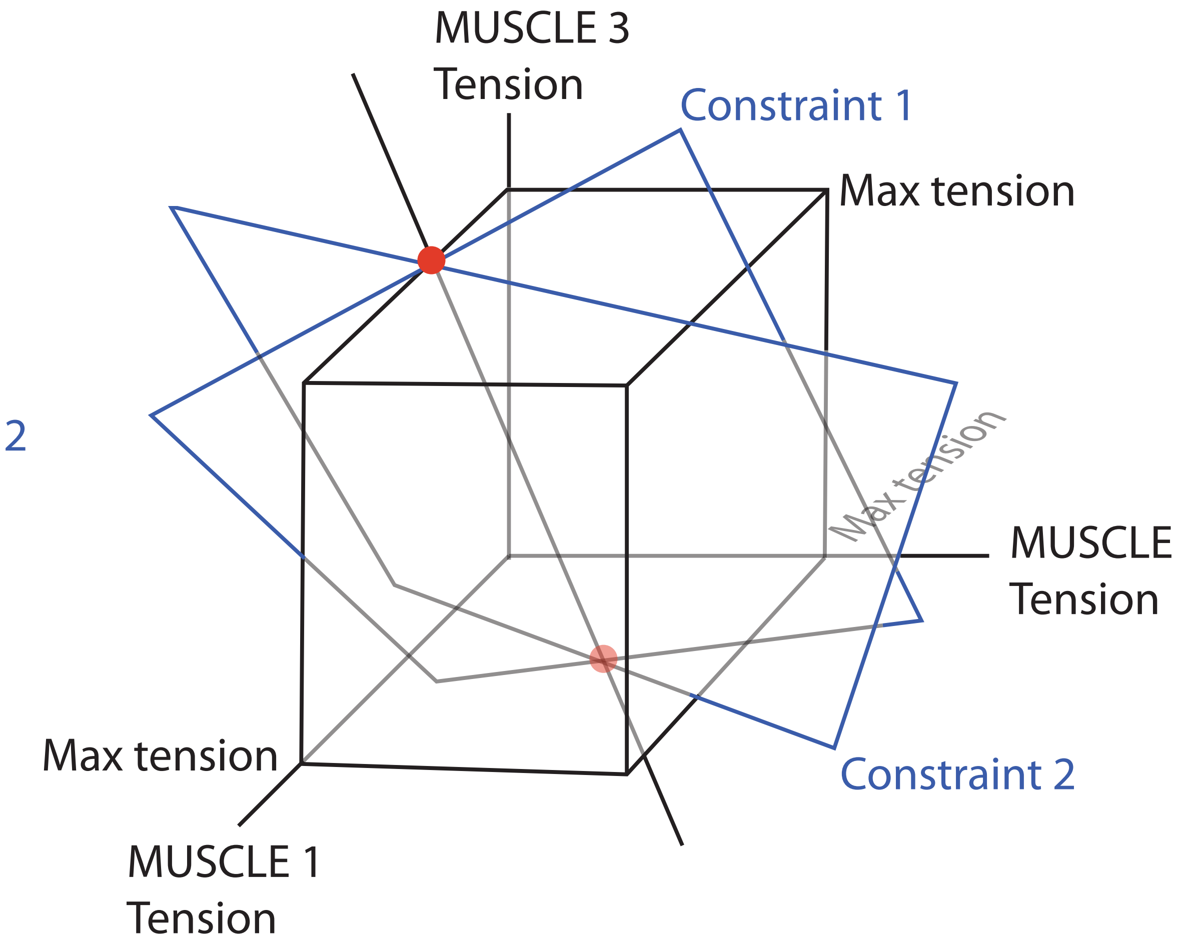

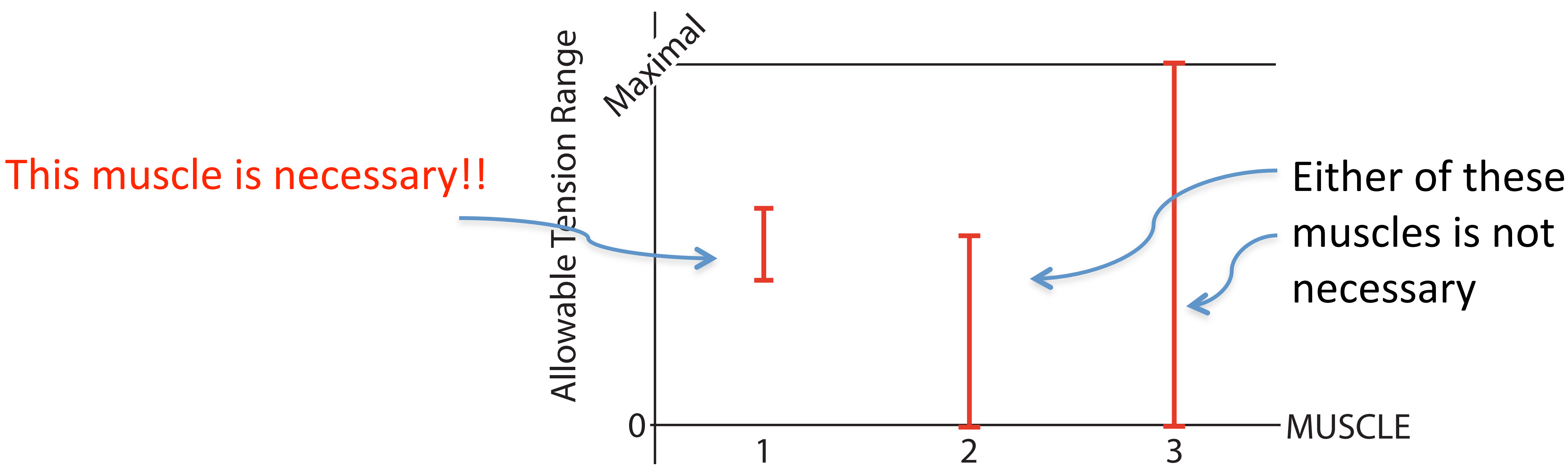

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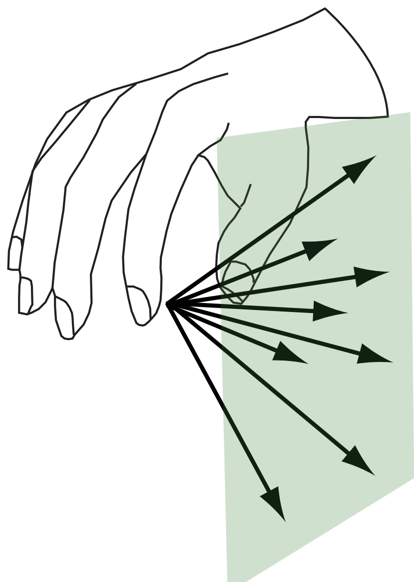
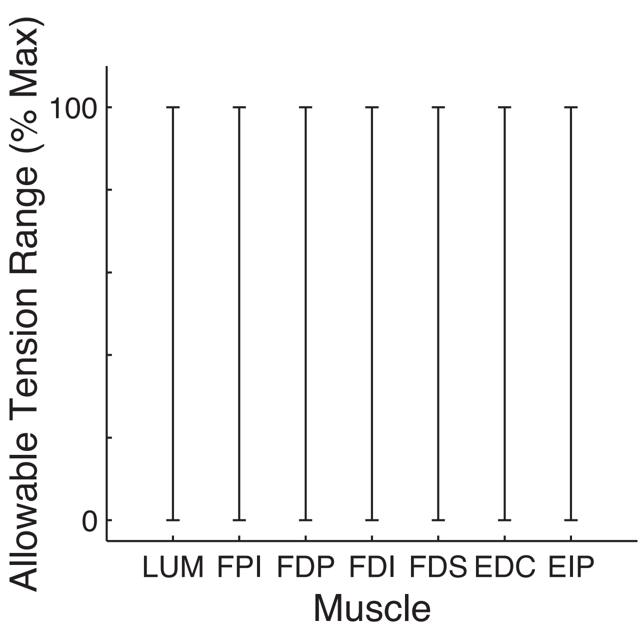
Kutch & Valero-Cuevas, J Biomech 2011

Example in 7-dimensional muscle activation space from real data

A. Constrain only radial force





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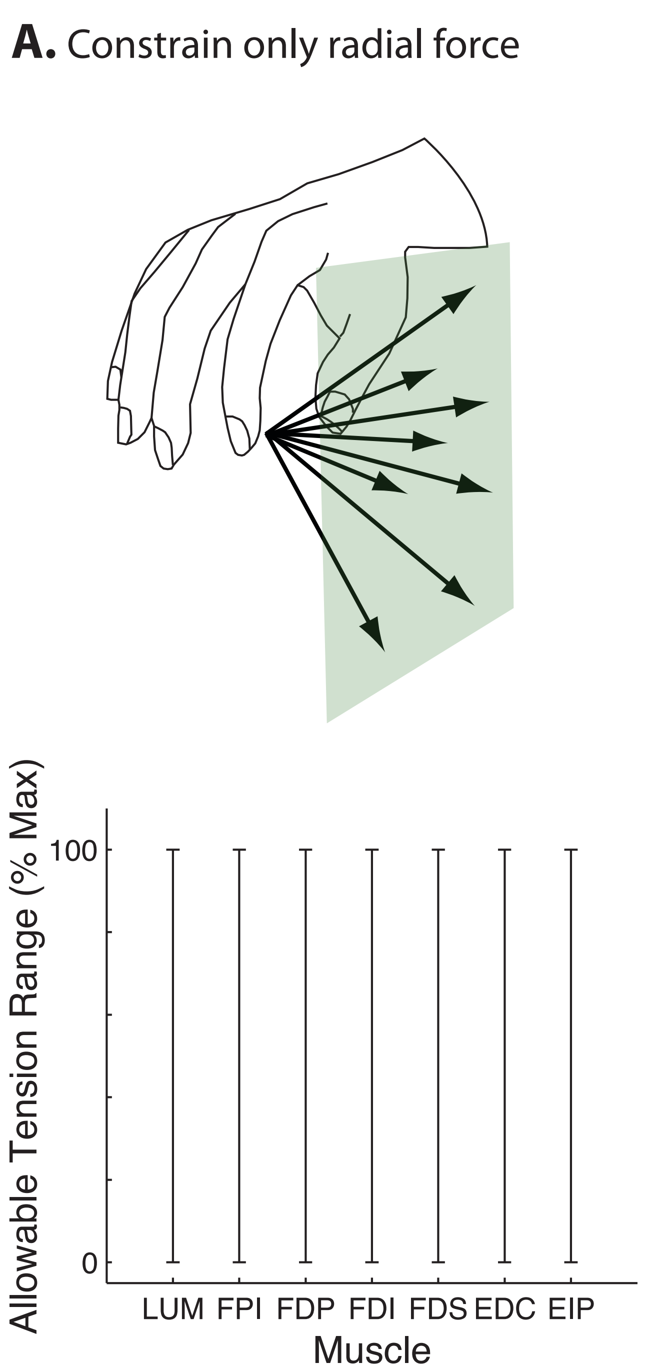

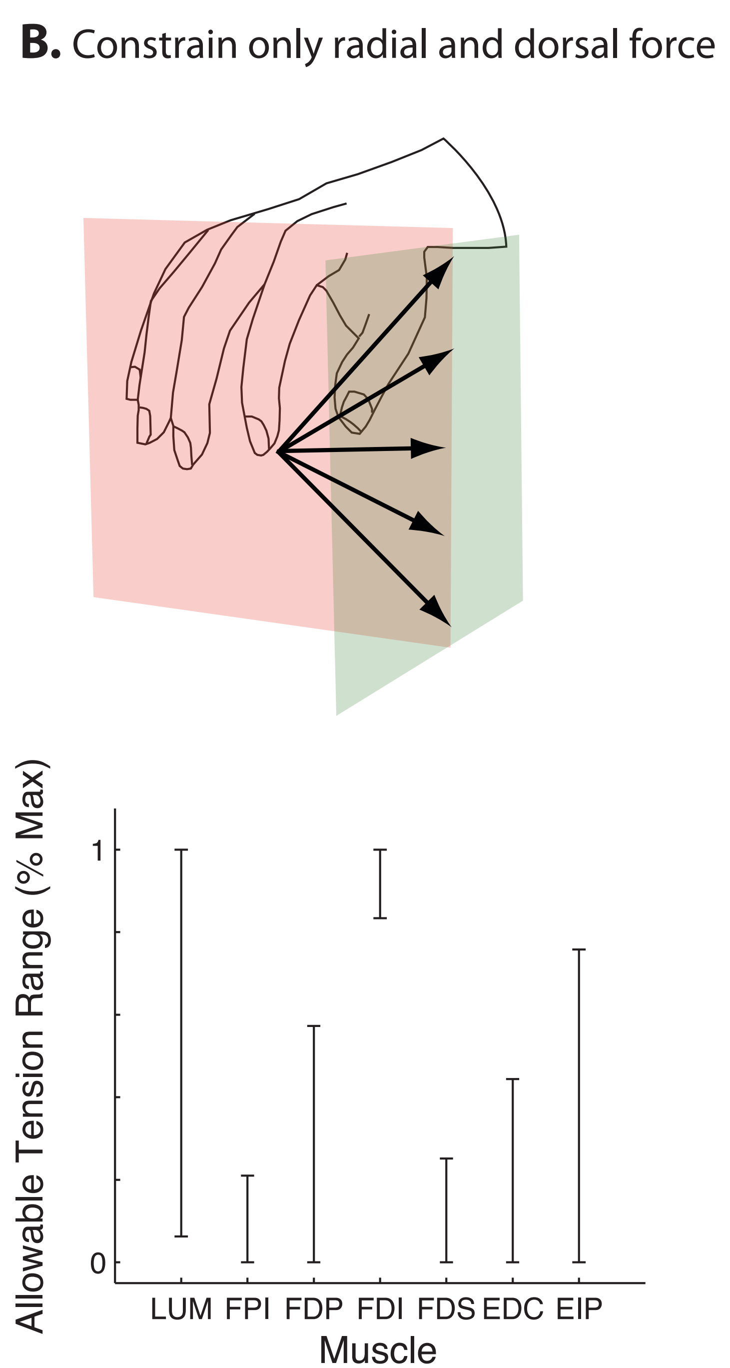

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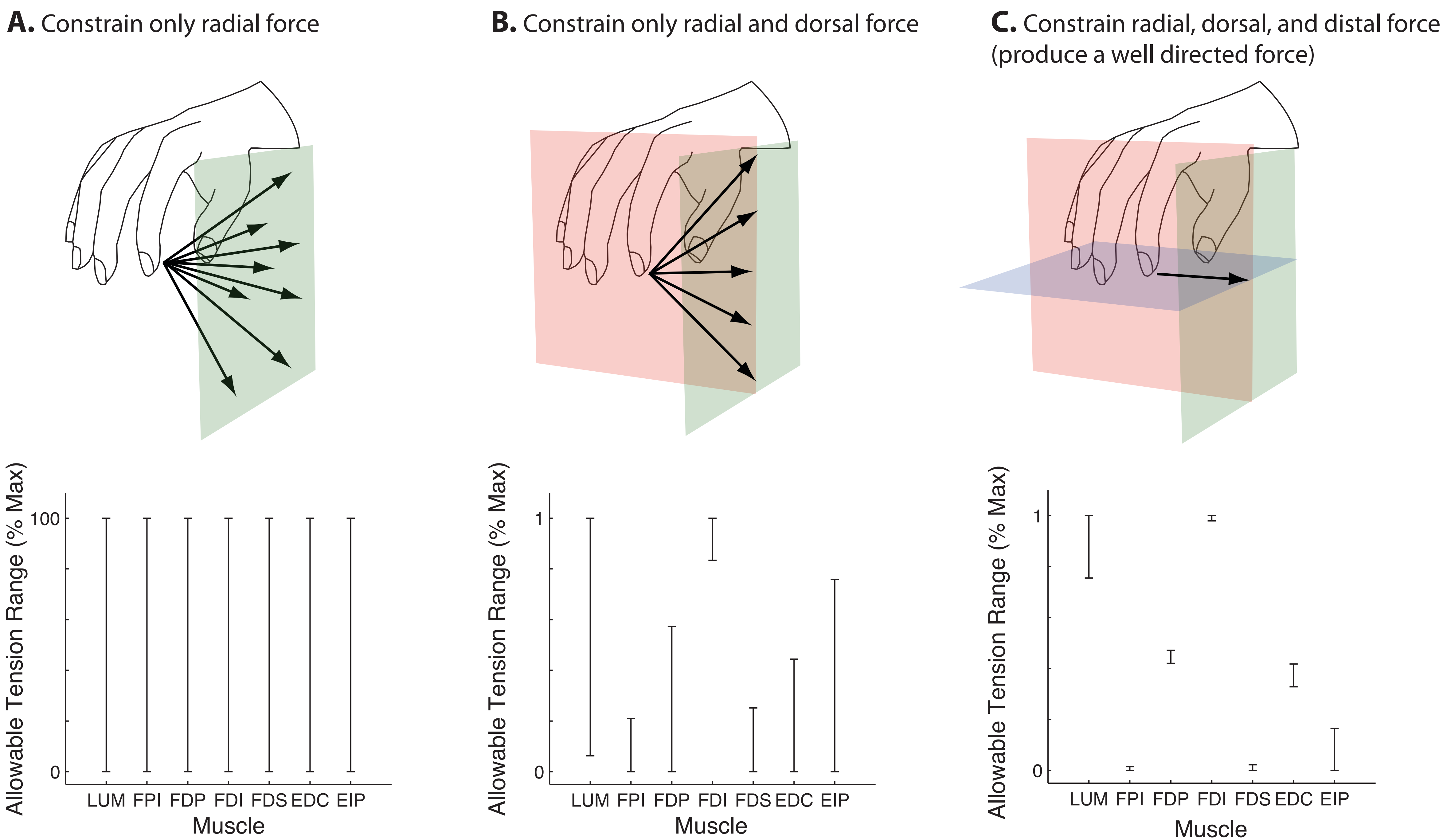

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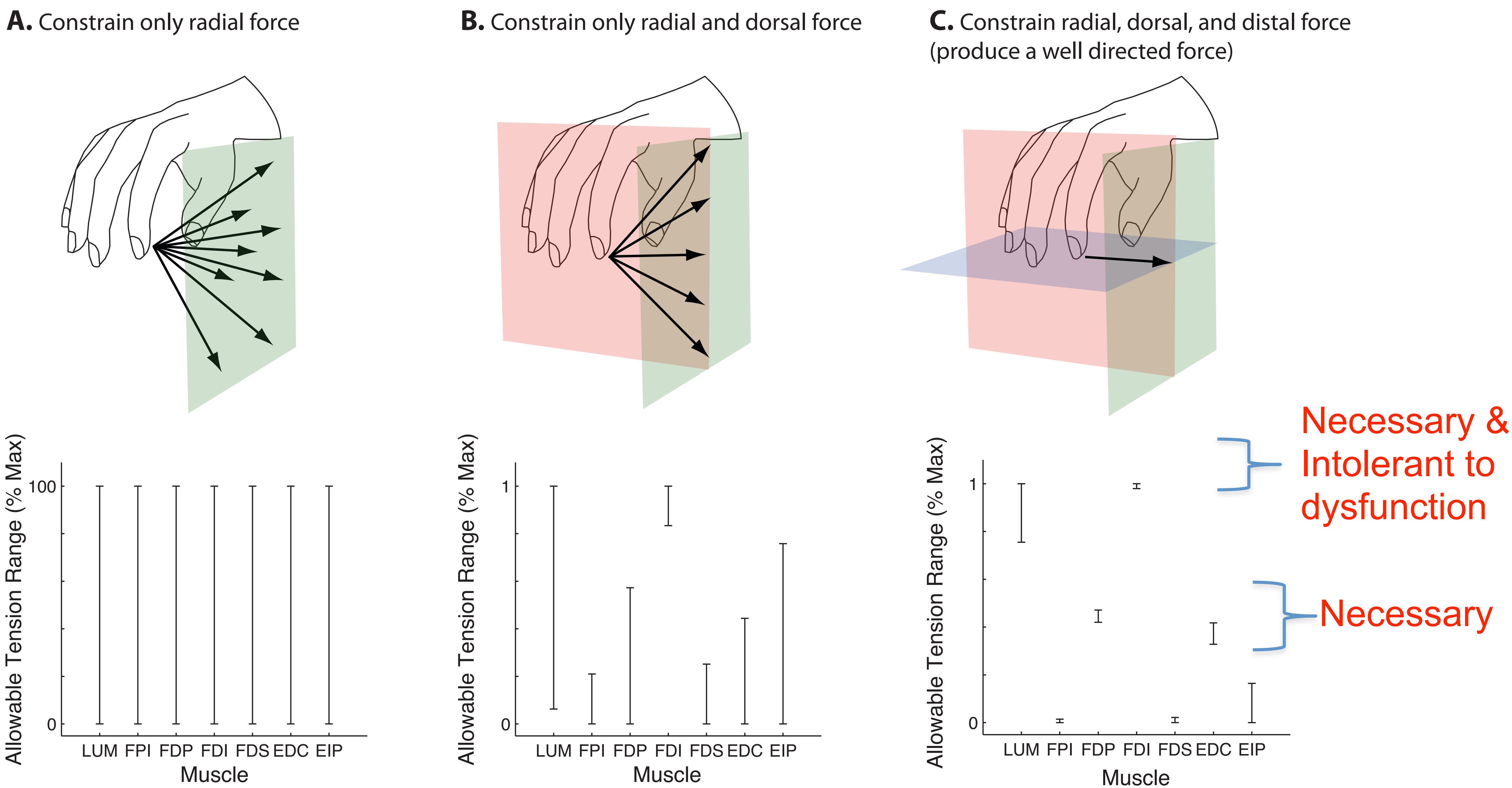
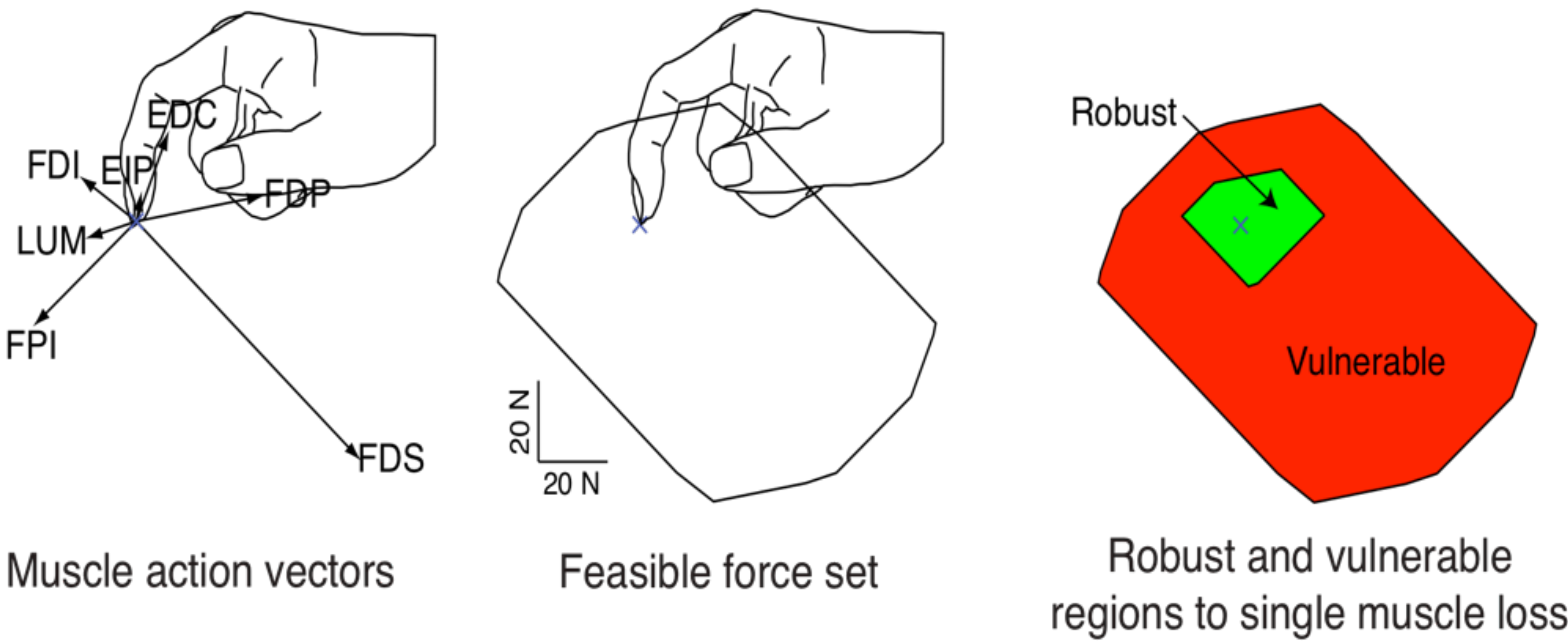


Robustness to single motor loss: Even for sub-maximal forces some muscles are necessary

Green region is what can be maintained if any one motor is lost



How robust are these results about robustness?

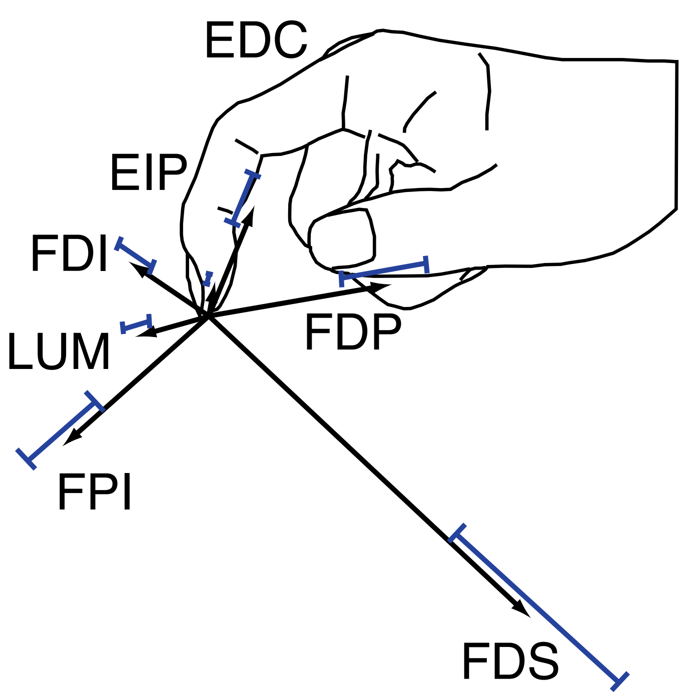
110 IEEE REVIEWS IN BIOMEDICAL ENGINEERING, VOL. 2, 2009

Computational Models for Neuromuscular Function

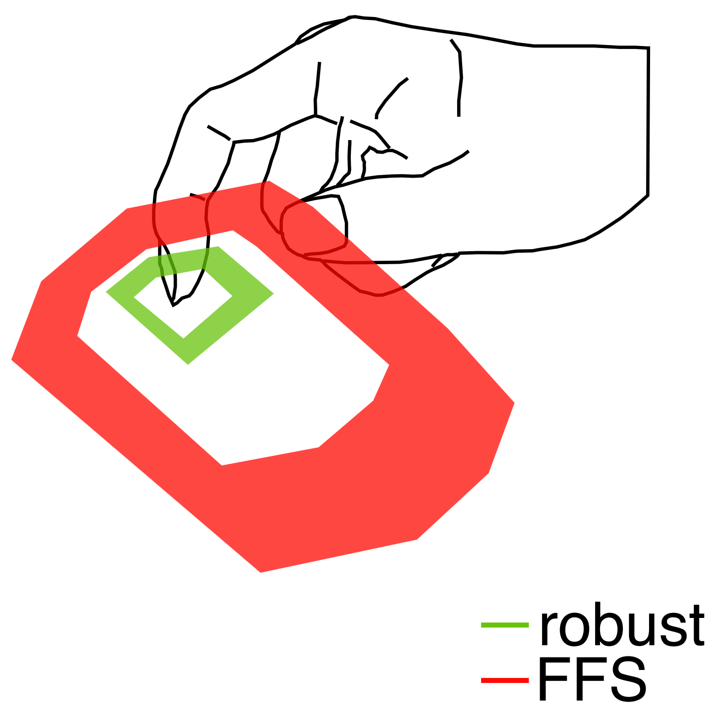
Francisco J. Valero-Cuevas, *Member, IEEE*, Heiko Hoffmann, Manish U. Kurse, Jason J. Kutch, and Evangelos A. Theodorou

Methodological Review

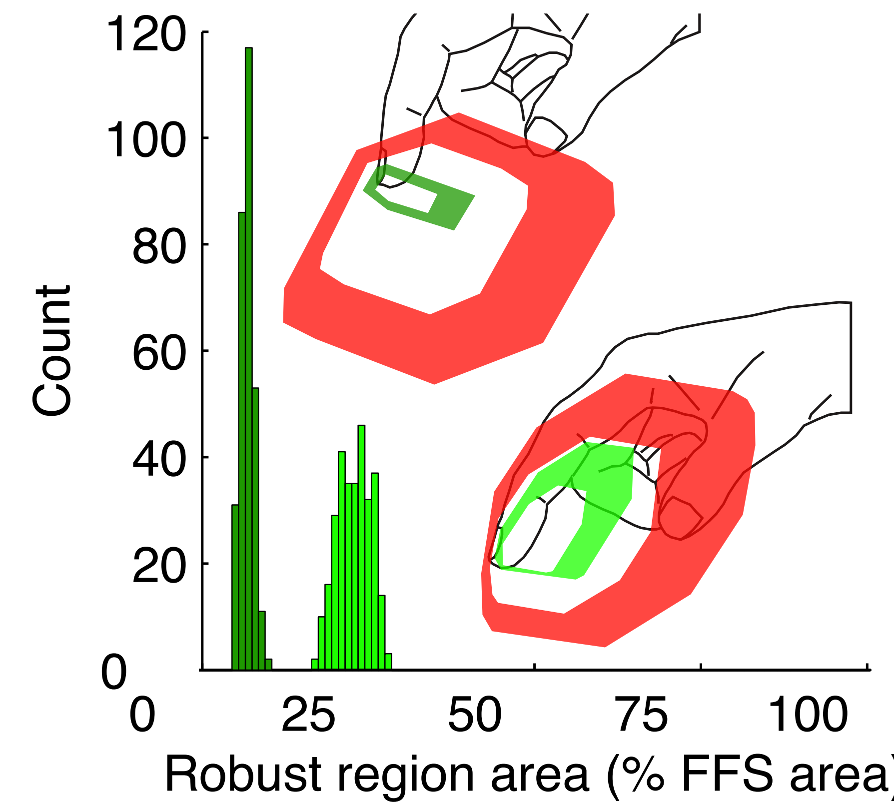
Even when perturbing experimental data and changing postures, it is never pretty!



± 25% changes
in muscle strength

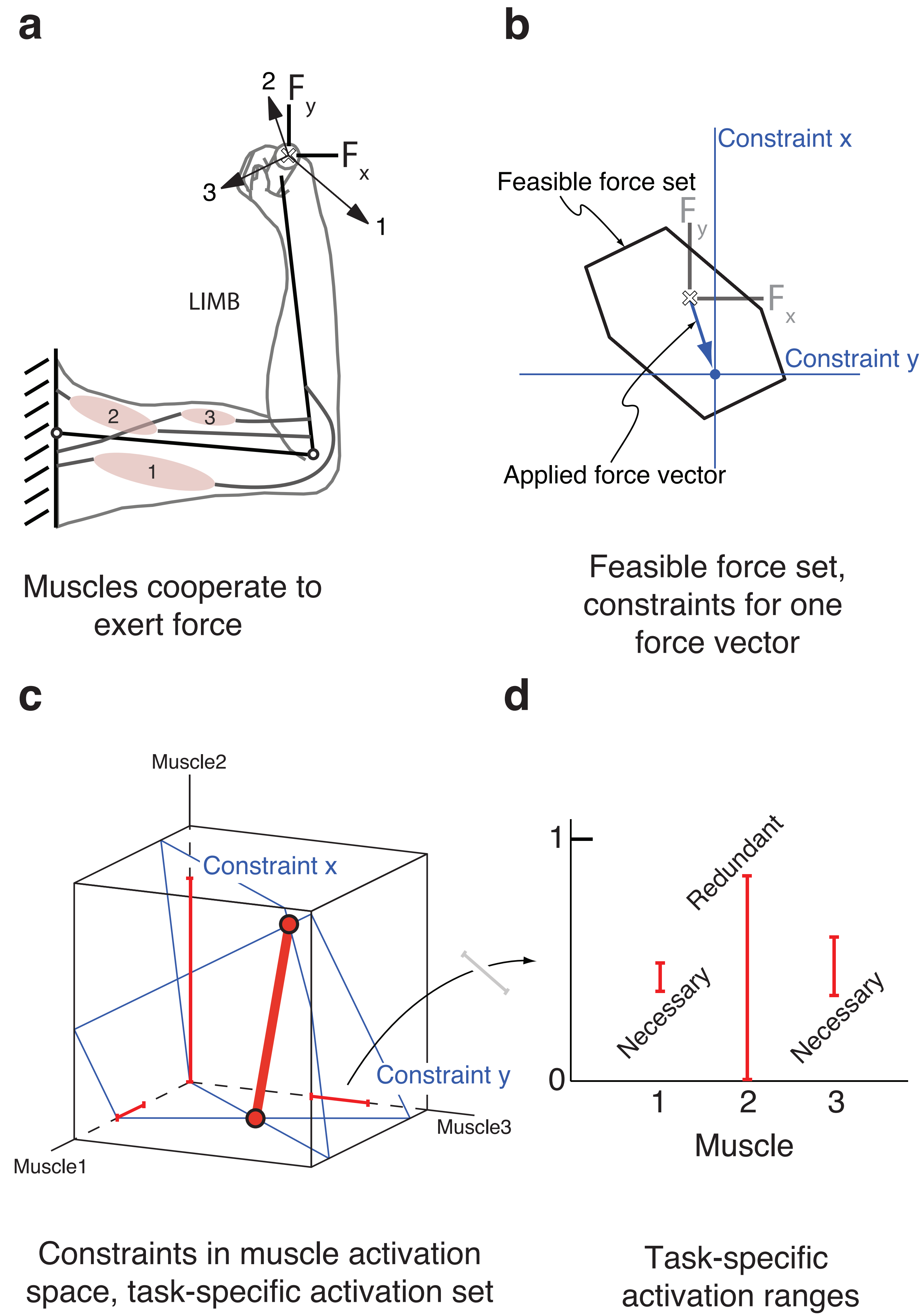


Changes in robust region
and feasible force set for
one specimen and posture



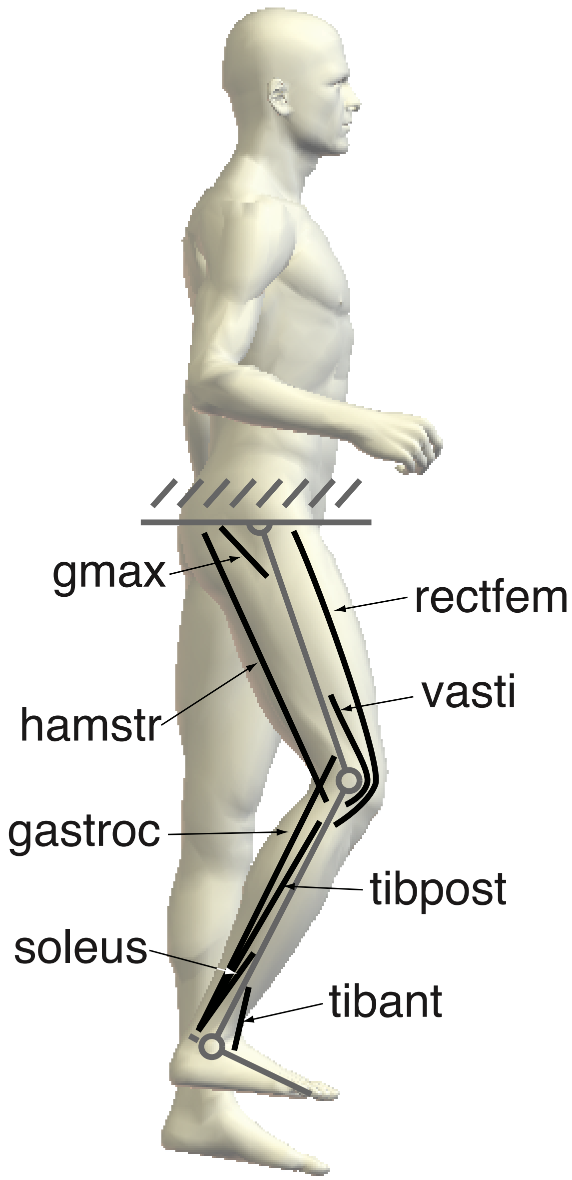
Smallest and largest robust region
for all specimens and postures

Kutch & Valero-Cuevas, 2011

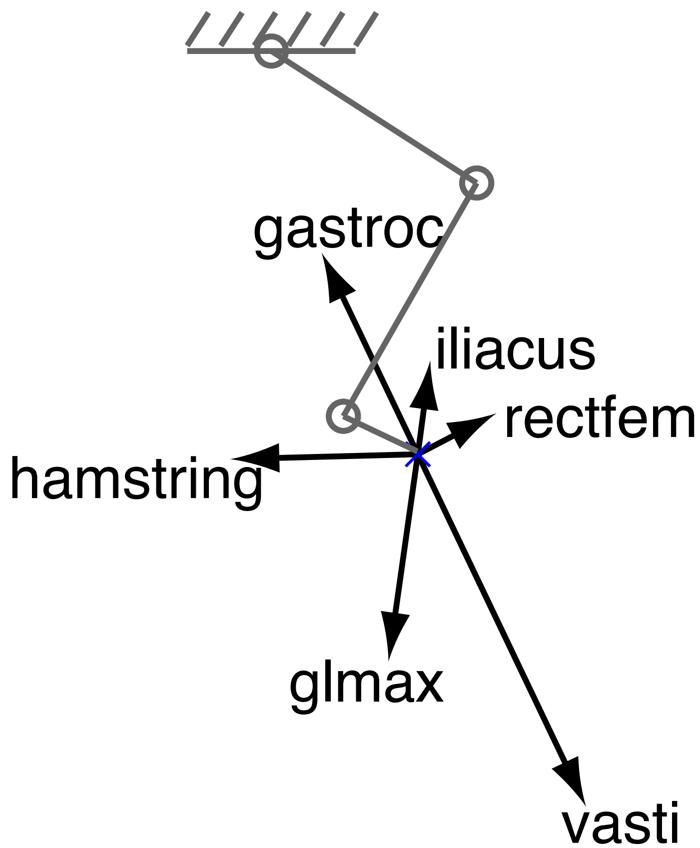


Another simulation example for different tendon routing and task

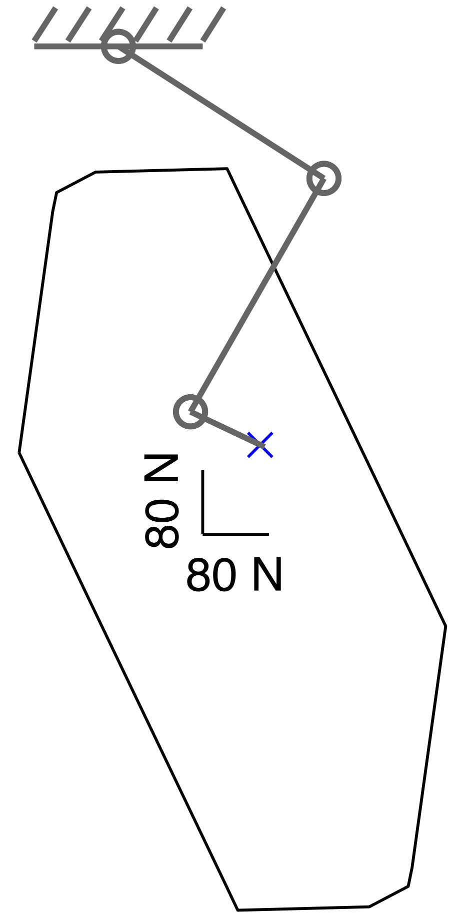
This result holds for any other tendon-driven system, such as a 14-motor leg



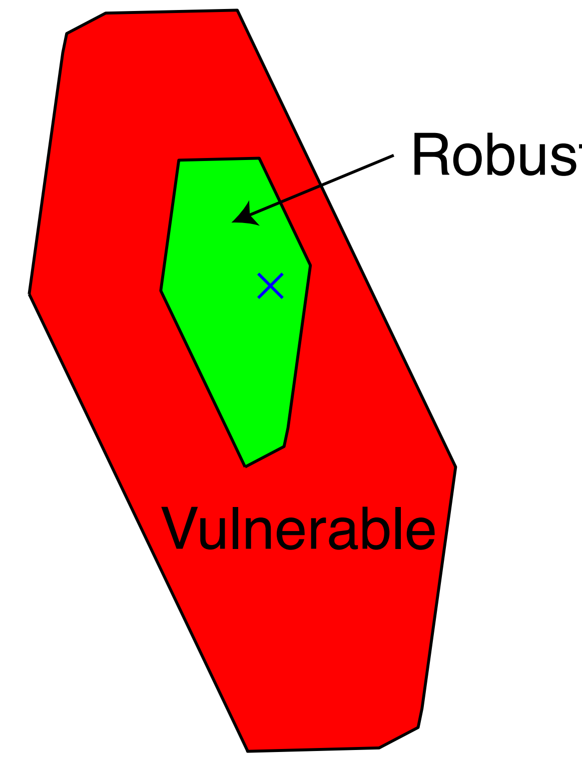
Sagittal Plane Leg Model



Sample muscle action vectors



Feasible force set



Robust and vulnerable regions to single muscle loss

Kutch & Valero-Cuevas, 2011

Another consequence for control

Is muscle co-activation always optional?

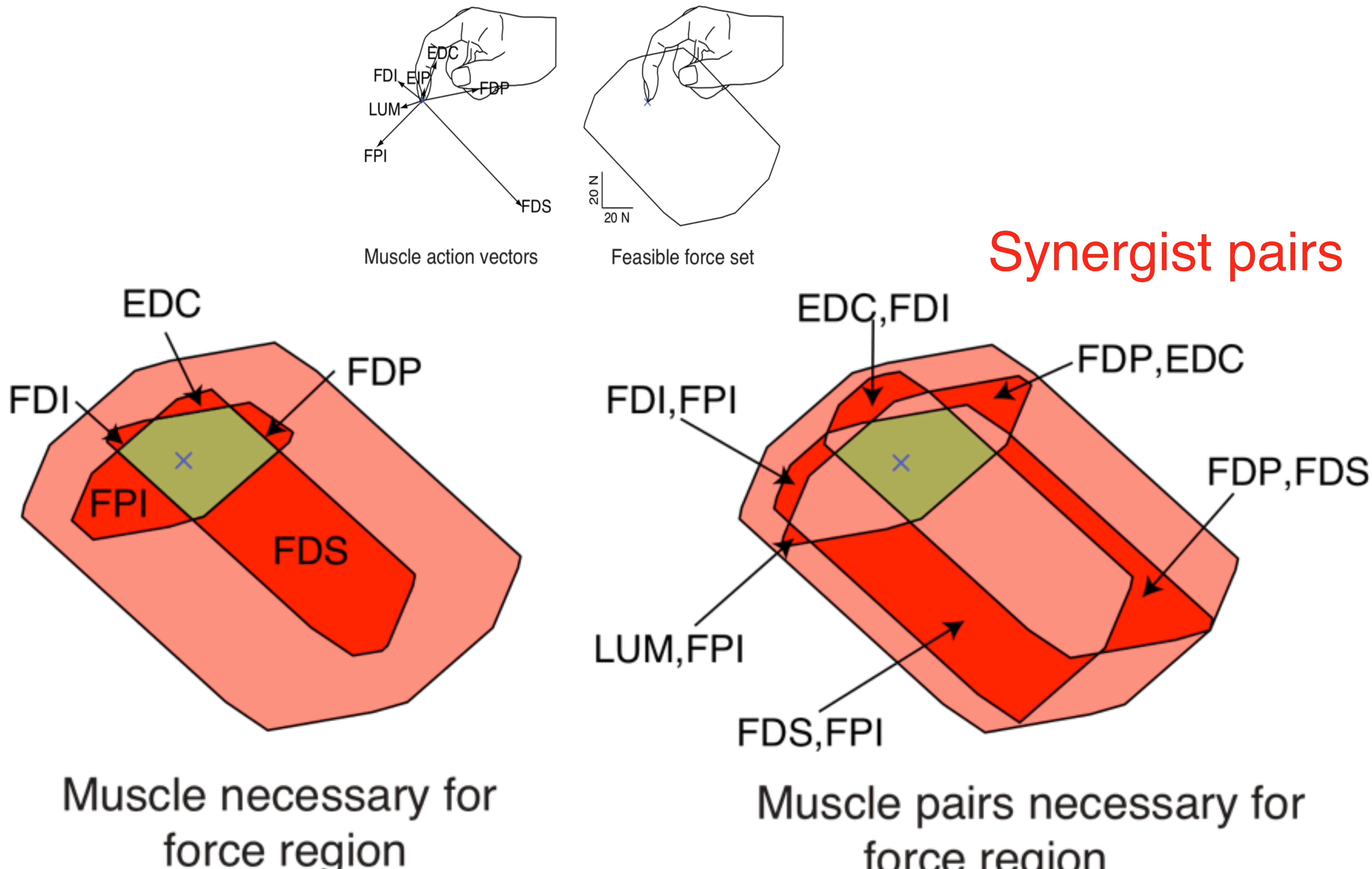
That is, what is the structure of “muscle necessity”

- for sub-maximal forces

and

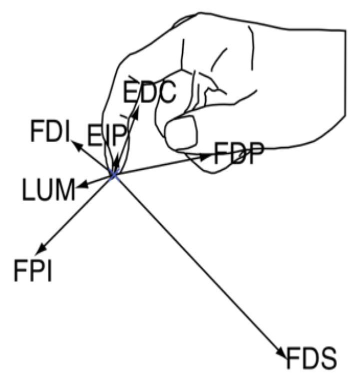
- for groups of muscles

For example:
Muscle pairs needed for sub-maximal output

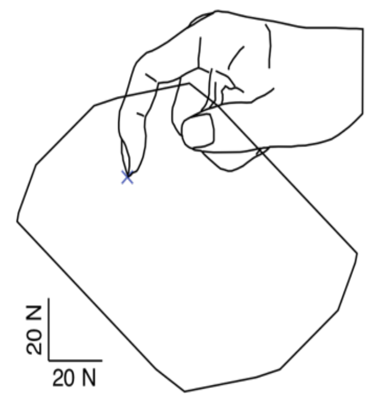


Synergist pairs

For example:
Muscle pairs needed for sub-maximal output

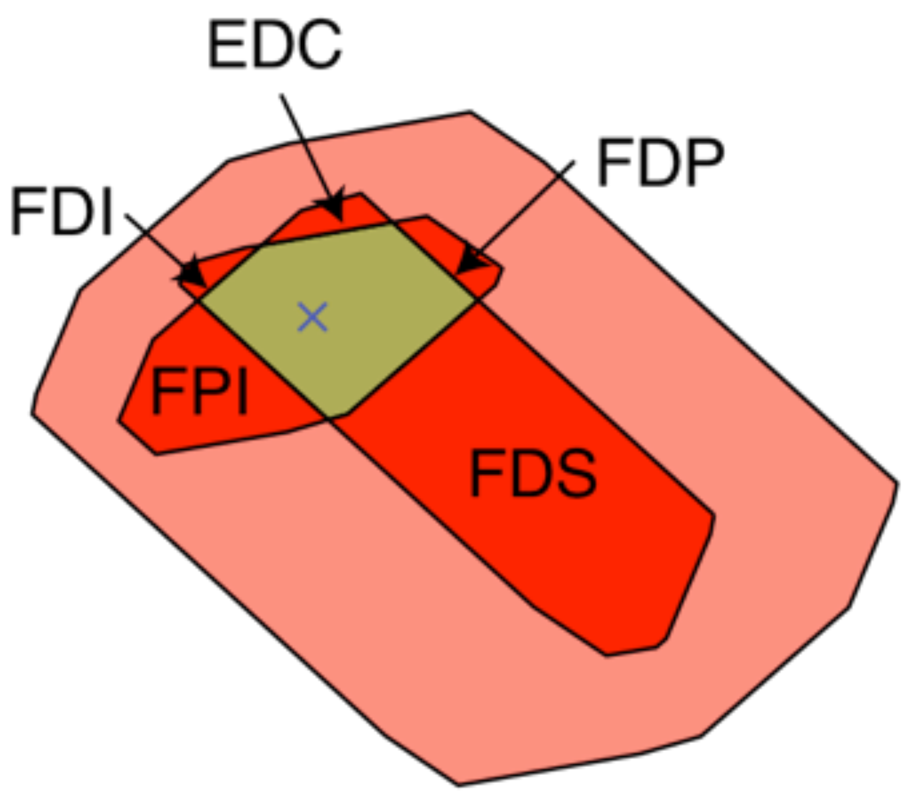


Muscle action vectors

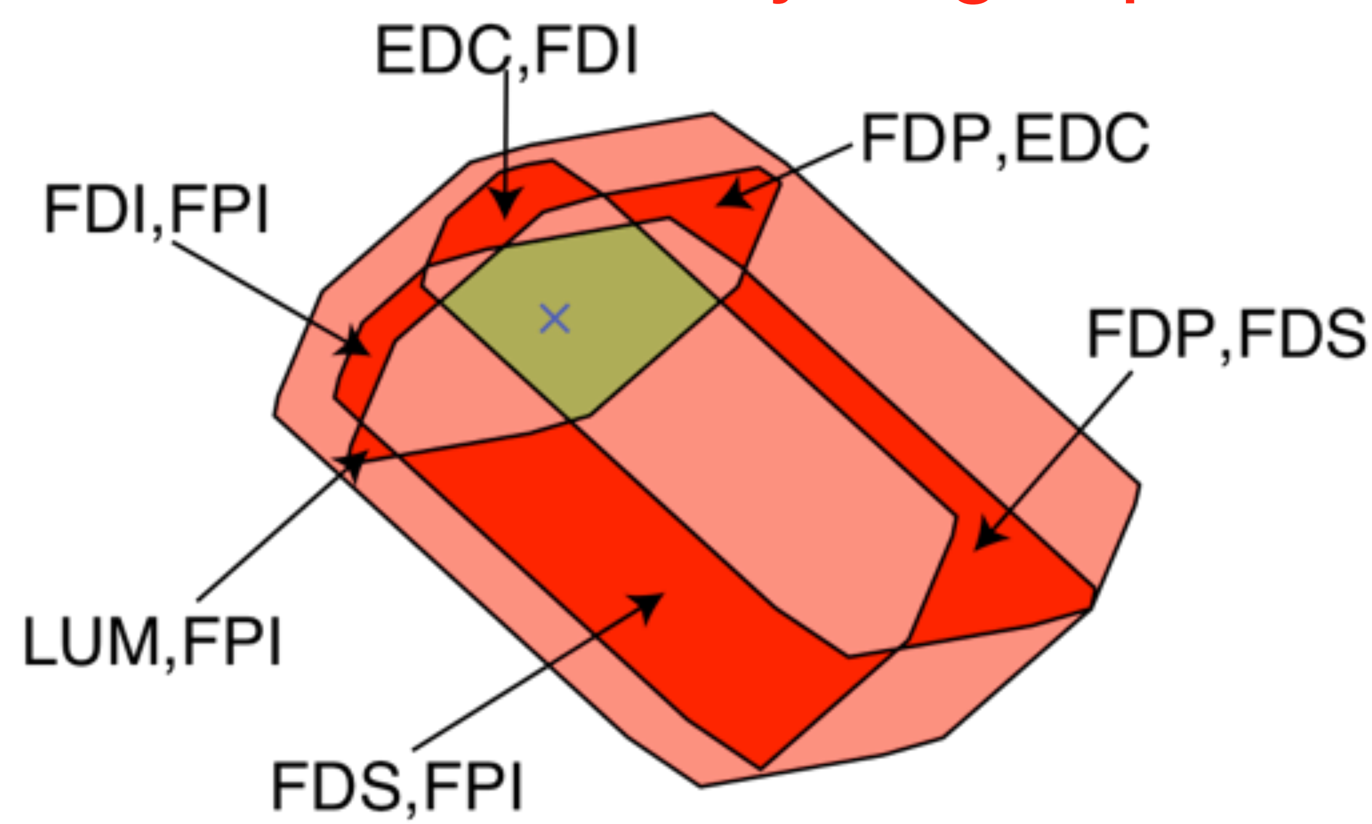


Feasible force set

Synergist pairs



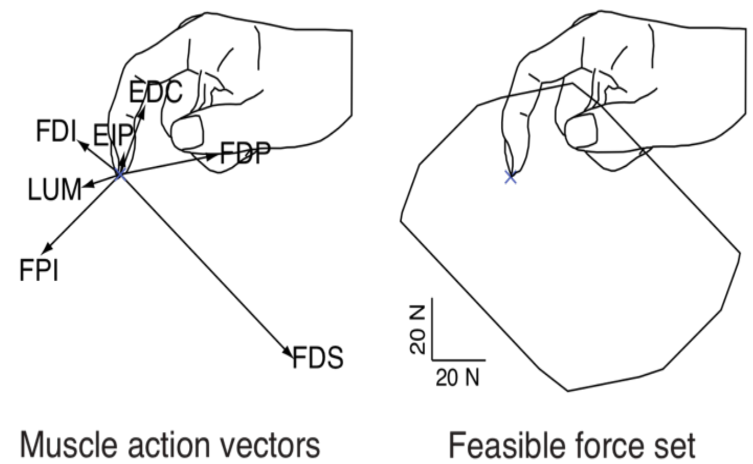
Muscle necessary for force region



Muscle pairs necessary for force region

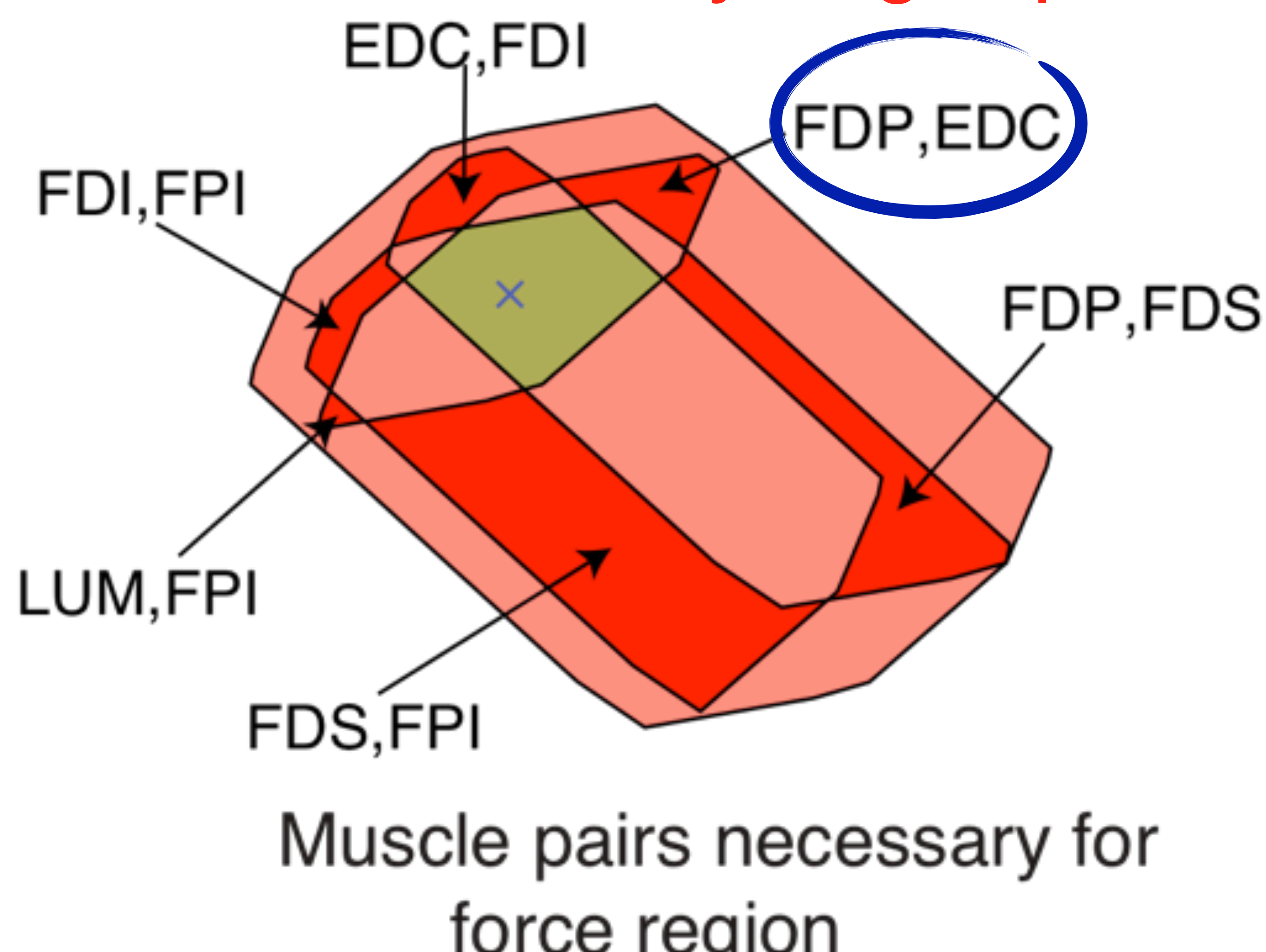
We can now describe the structure of the solution space!

For example:
Muscle pairs needed for sub-maximal output



Synergist pairs

"Anatomy Lesson of Dr. Tulp", by Rembrandt, 1632

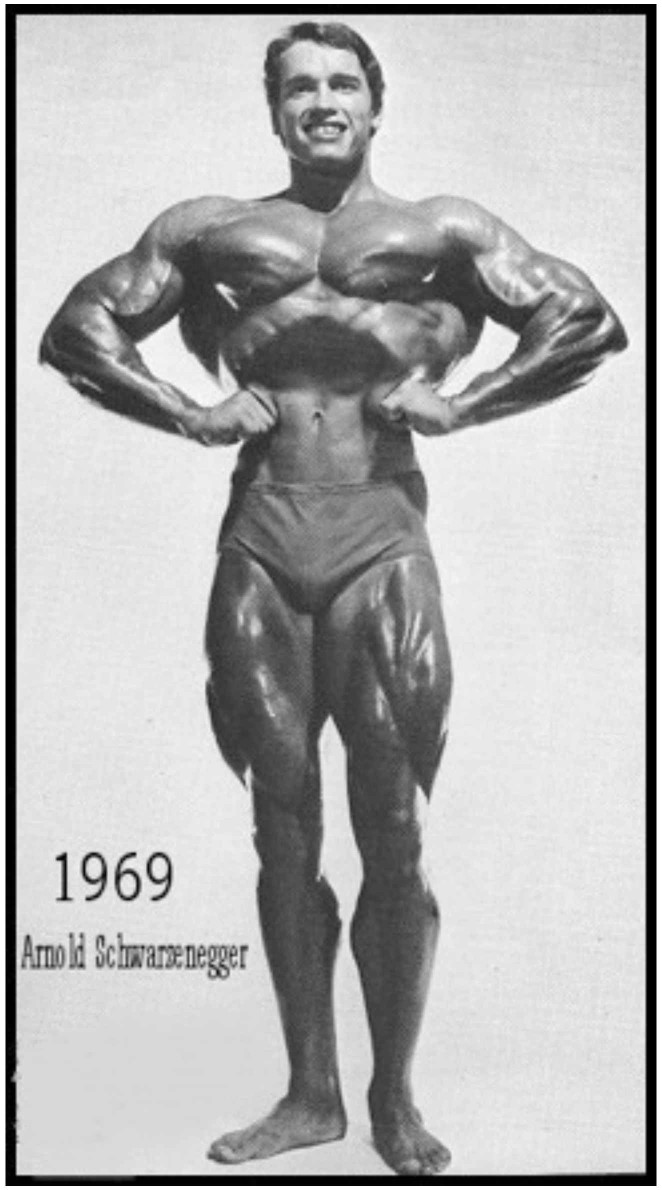


But the language inherited from XV century anatomists fails us

This begs the questions:

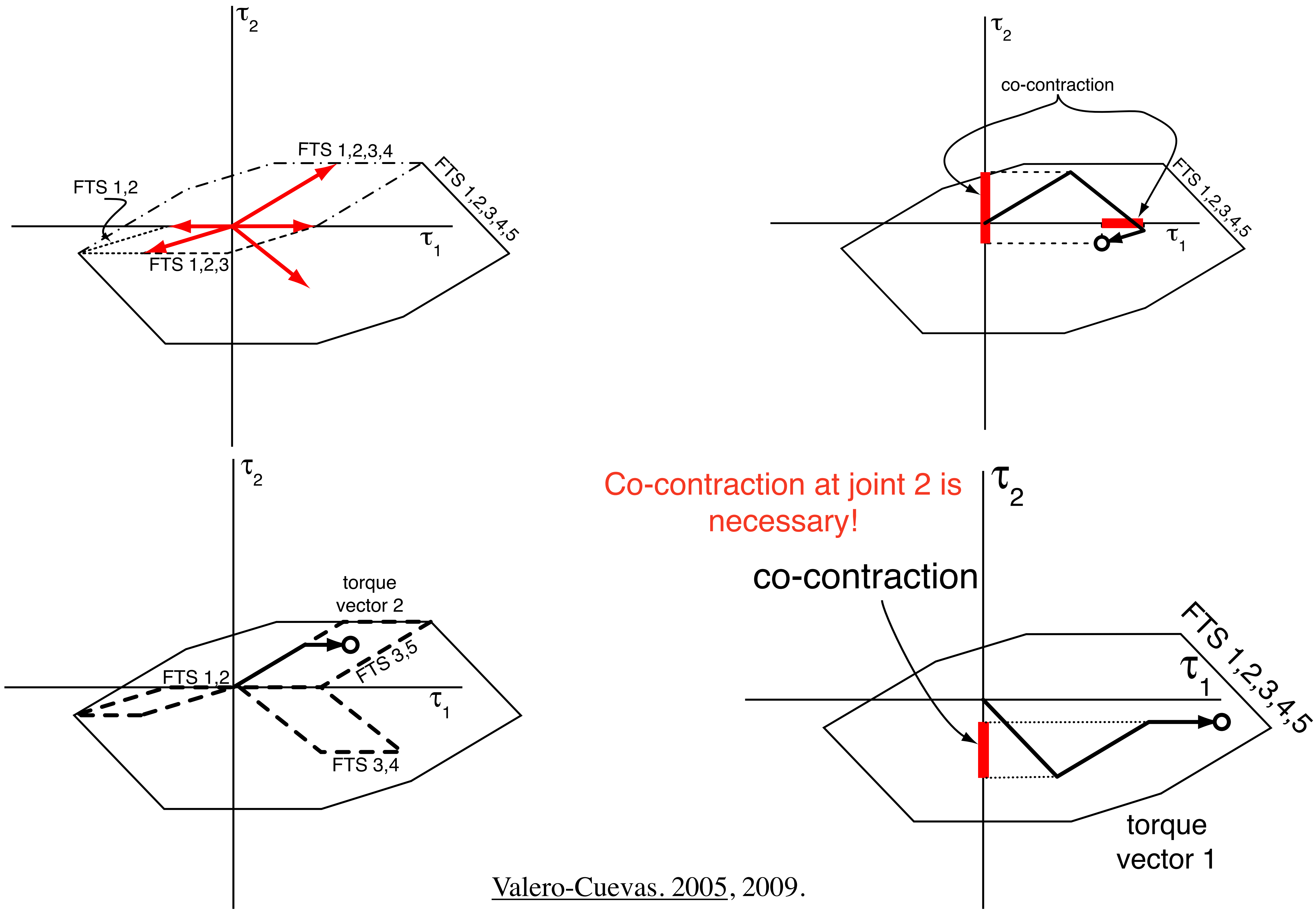
What are agonist-antagonist pairs?

Is co-contraction always optional?



Valero-Cuevas. 2005, 2009.

Controlling muscles is like herding cats, and co-contraction is back-tracking in torque space



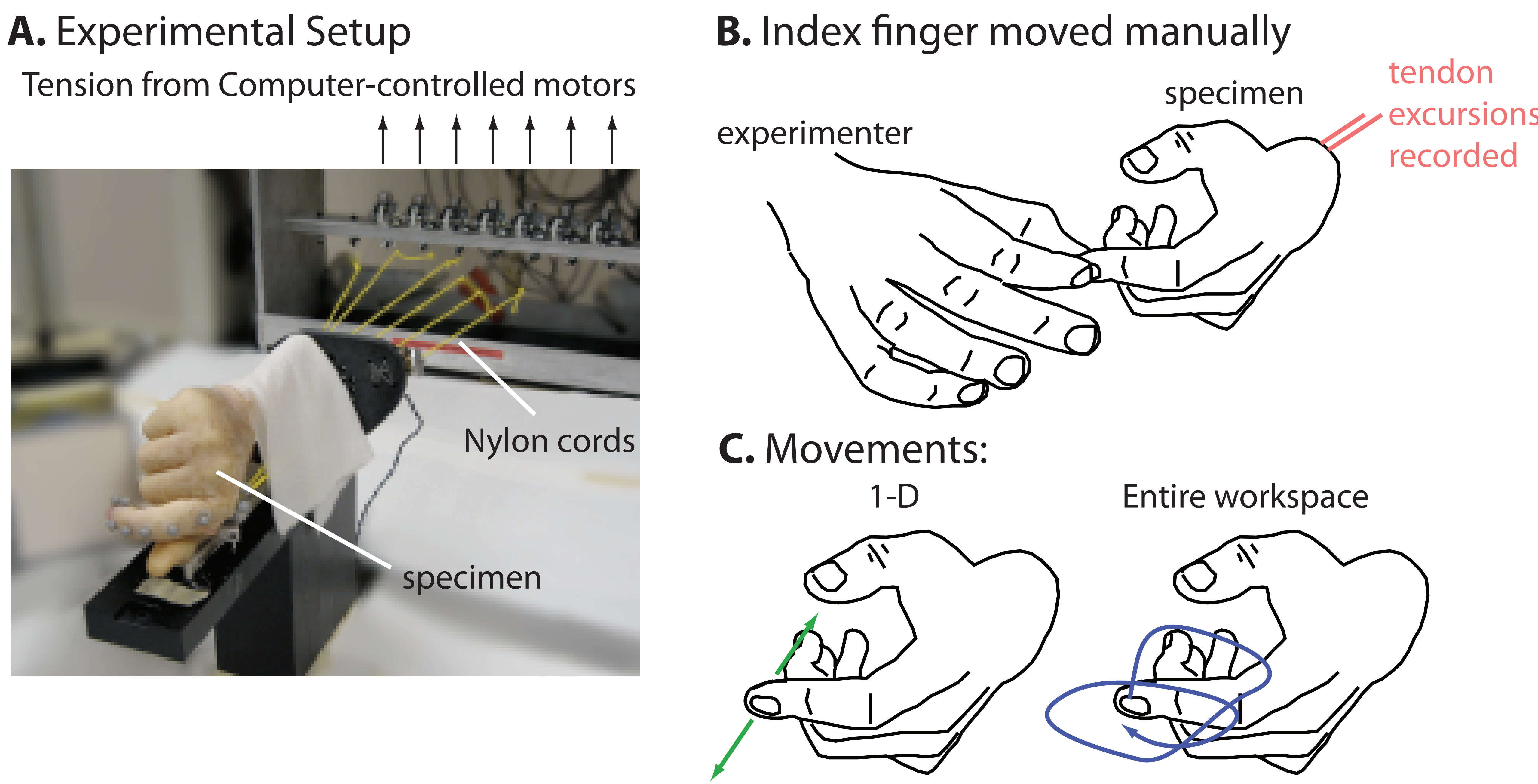
Valero-Cuevas. 2005, 2009.

Another consequence for control

High-dimensional co-variation: Muscle Synergies

When can muscle synergies be attributed to the nervous system vs. the neural control policy?

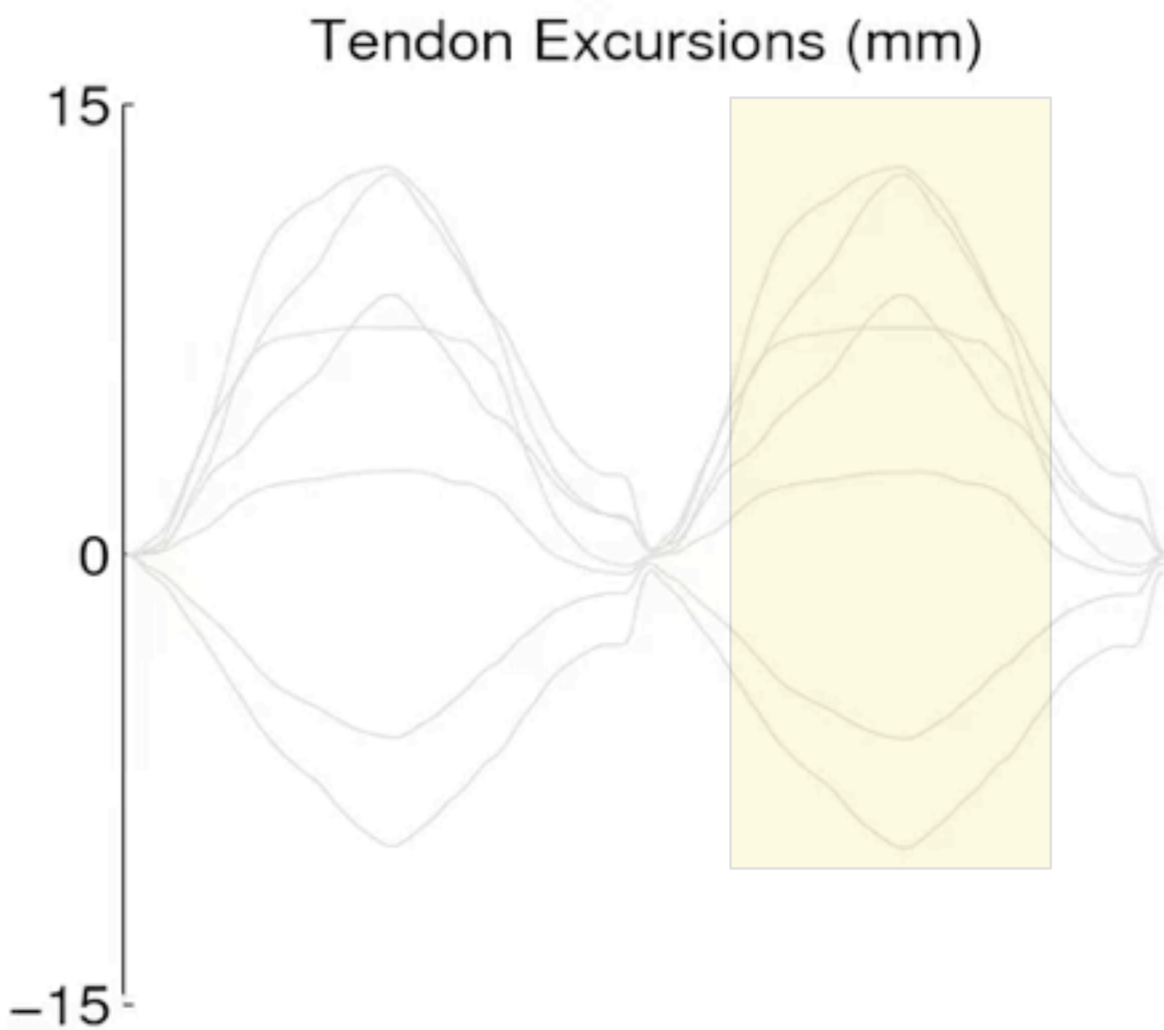
Recent work:
Measurement of movement related interactions across muscles

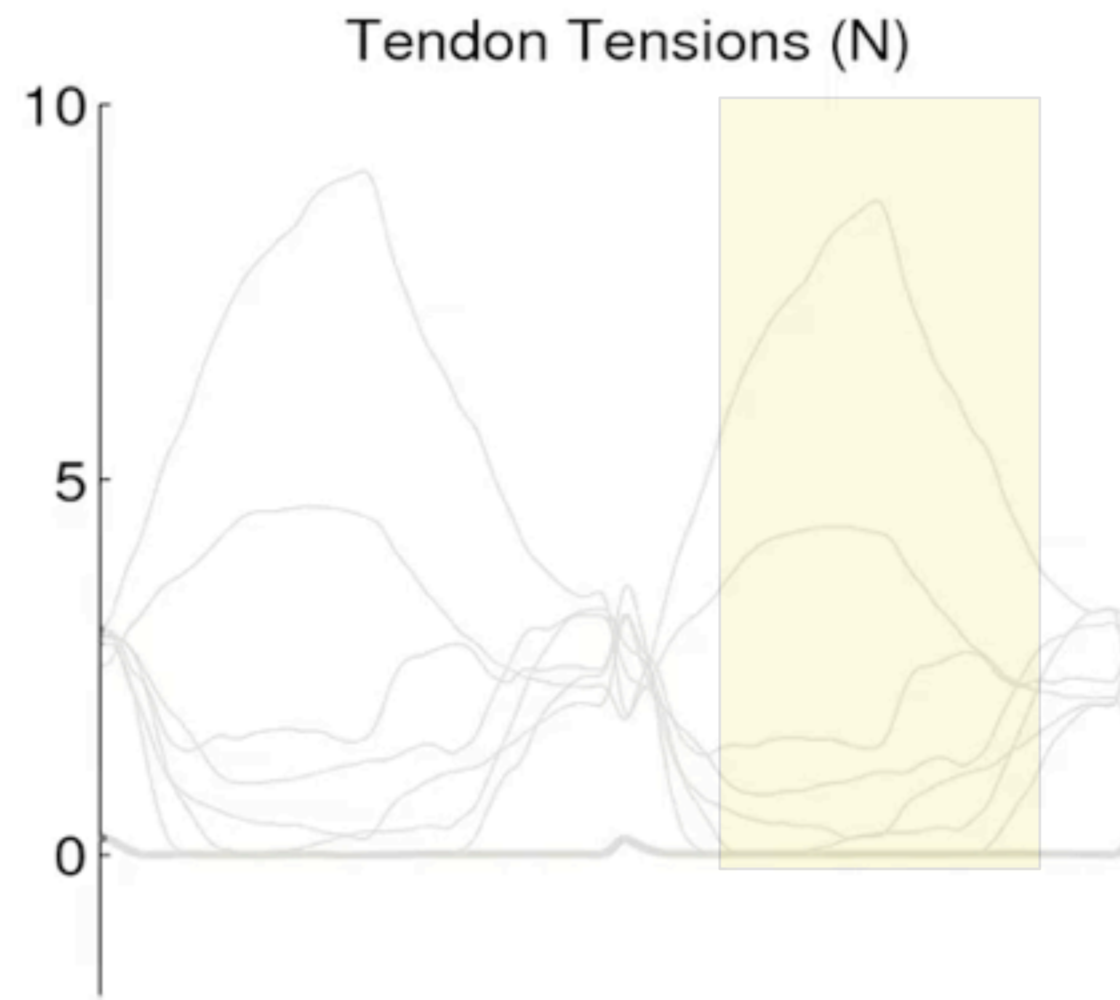


Kutch and Valero-Cuevas, In review

The first computerized actuation of all tendons of a human finger, 2009

One possible u(t) when muscles are implemented as tunable springs





Note the complex association between excursion and force (...and thus EMG!)

Knowing the structure of the solution space enables testing for the existence of muscle synergies of neural origin

Available studies have not been able to disambiguate neural vs. non-neural high-dimensional covariation of muscle interactions.

Conclusions about
Over-, under-, or exact-actuation

Often called the central problem of sensorimotor neuroscience, but we need to be very careful about terms and their meaning.

Summary about over-, under-, or exact-actuation

- Versatility requires redundancy
- Redundancy does not imply robustness
- Every muscle contributes uniquely to function

From the structure of the task solution space we now see:

- Co-contraction is often not an option
- Agonist-antagonist language loses meaning
- Synergist muscles may not be obvious
- Can design tests for the existence of synergies of neural origin

Valero-Cuevas, 2009

Valero-Cuevas, 2004

Valero-Cuevas et al, 2009

Kutch and Valero-Cuevas, 2011

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