Towards the right “*hardware*” (anatomical and neural): Human hands

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RSS 2014 WORKSHOP - HUMAN VERSUS ROBOT GRASPING AND MANIPULATION

Homo sapiens

Our identity as a species is largely associated with specializations for

Behavior in the physical world!

cognition | speech | manipulation

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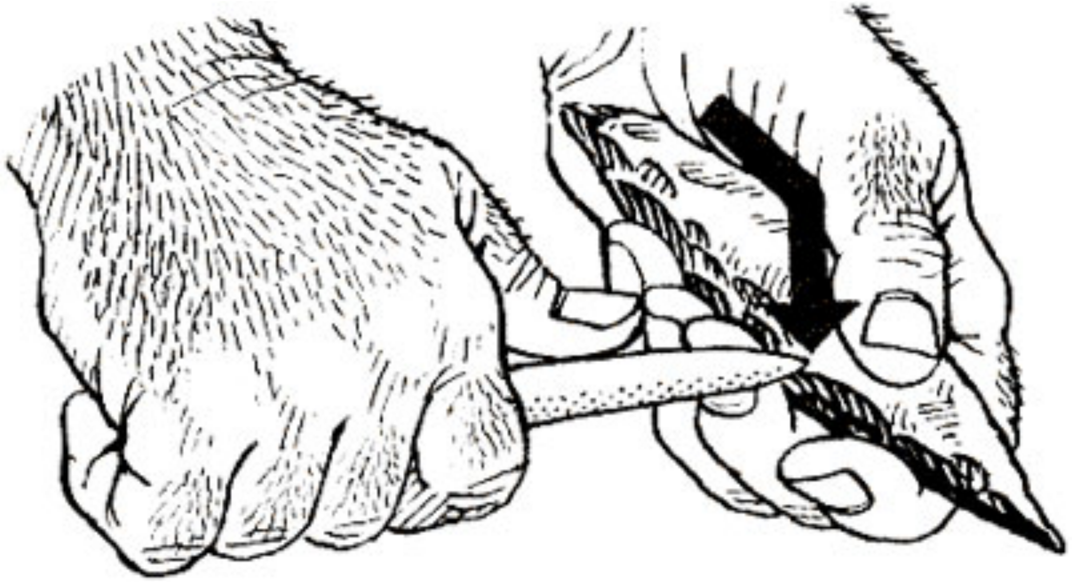

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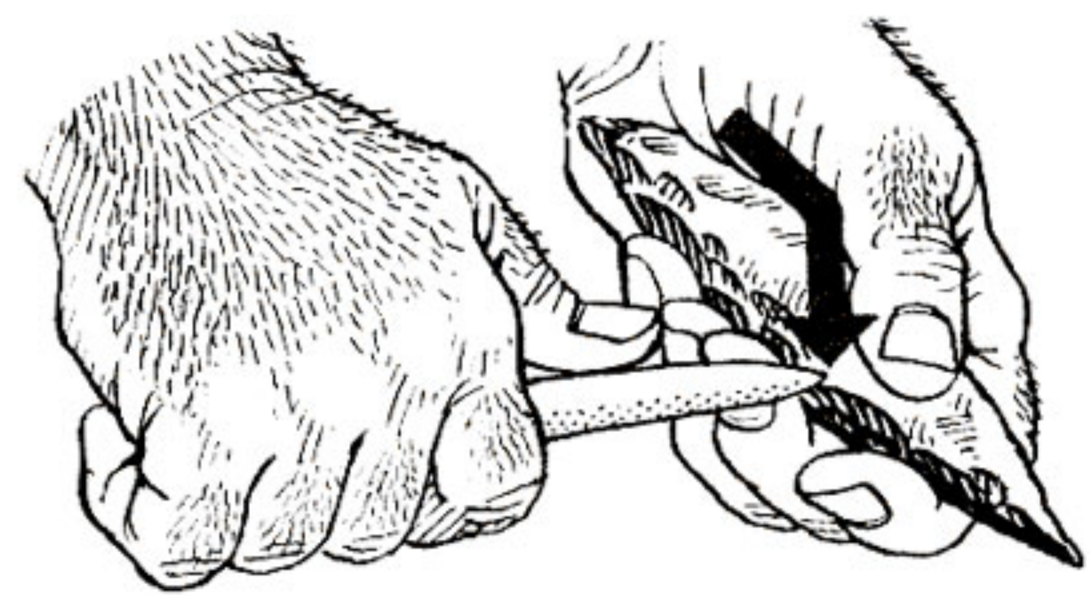

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Some long term questions about physical behavior

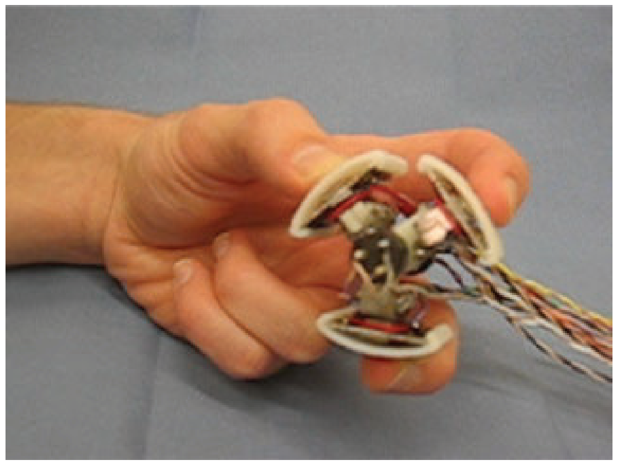
How does the neuromechanical system (or how should a versatile machine) meet the necessary and sufficient conditions for dexterous function?

and/or

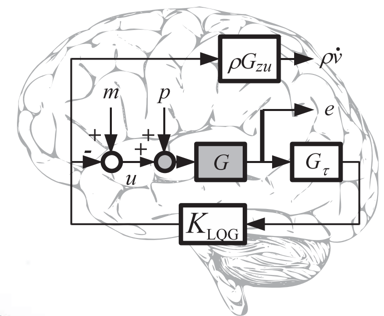
What specific contributions from passive (e.g., the body/hardware) and active (e.g., the brain) components enable dexterous function?

My scientific approach to these problems

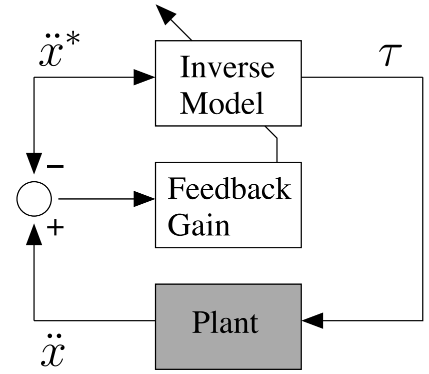
Sensorimotor behavior

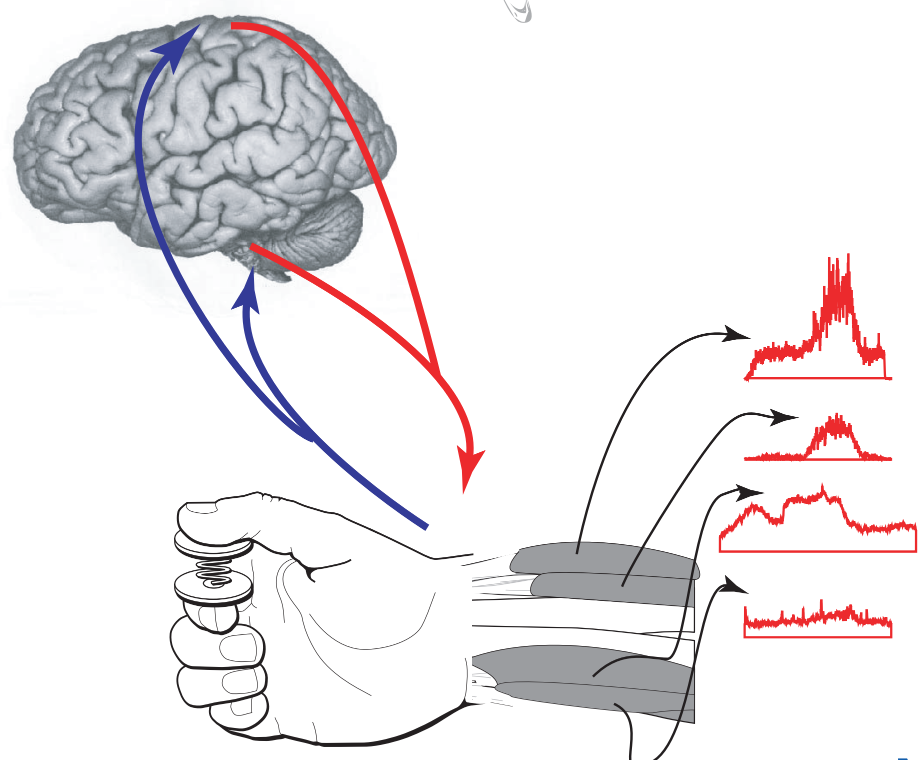


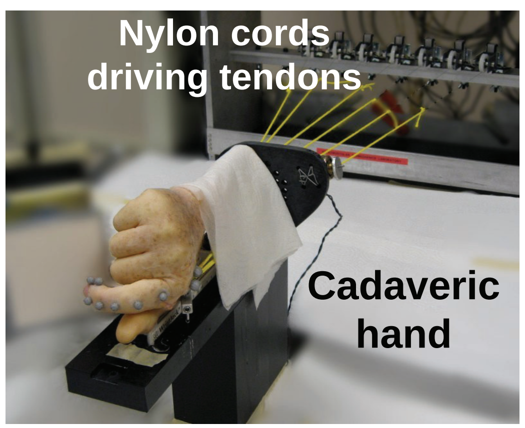
Theories of neural control



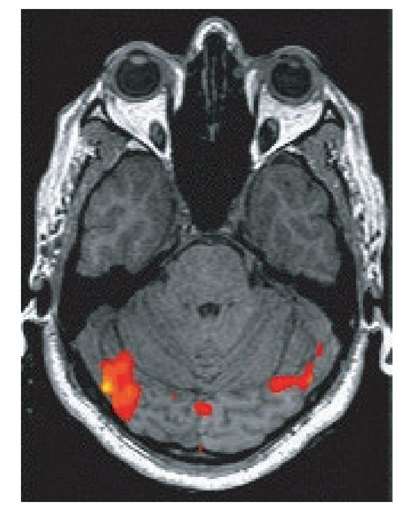
Machine learning



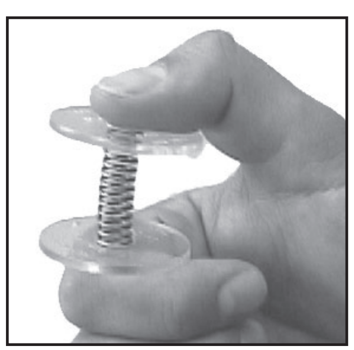




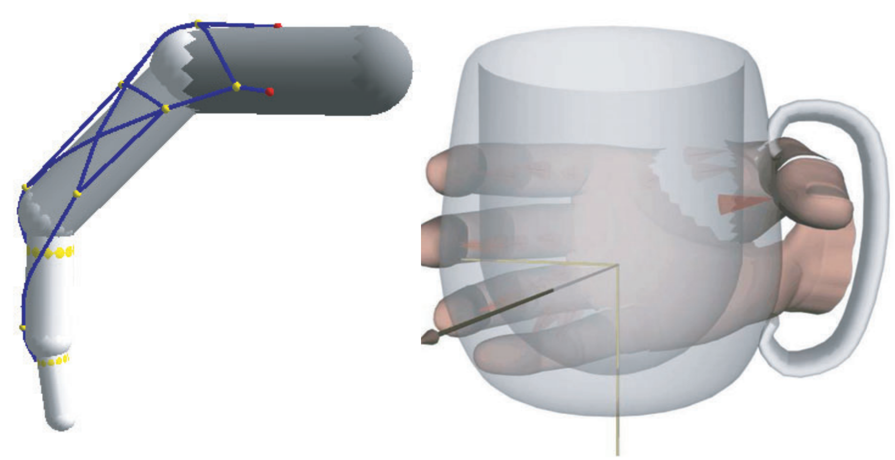
Physical modeling



Neurophysiology



Clinical and rehabilitation tools



Musculoskeletal modeling

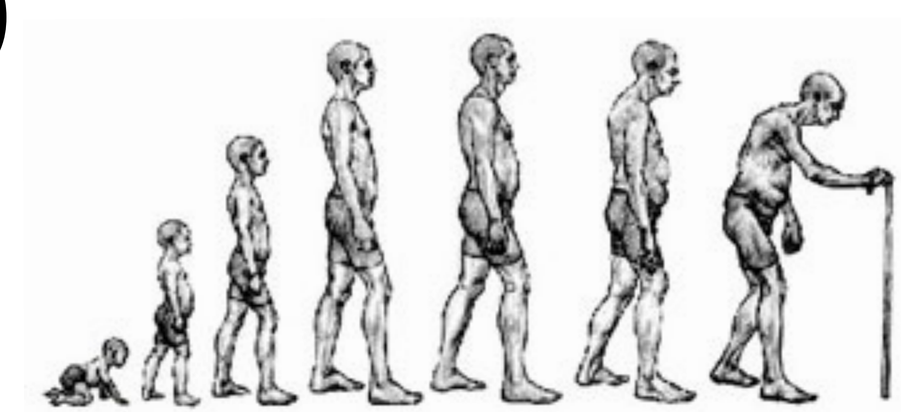
Purpose of this talk

To be informative, but also provocative, about the interaction between mechanics and neural control for dexterous function.

Something we call
Neuromechanics

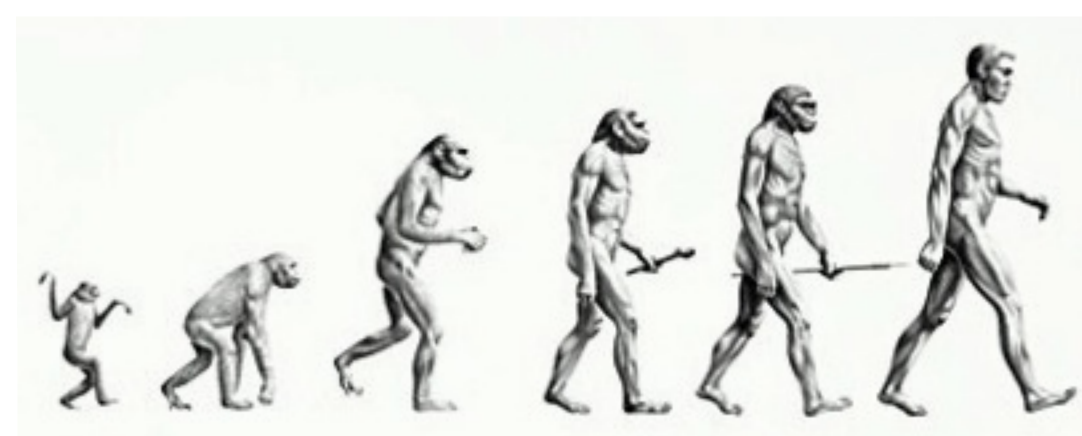
I approach these question as

What problem is the brain *really* solving every day of our lives? (Newtonian)



or

What *co-evolutionary* pressures drove the development of brain-body systems? (Darwinian)



Disclaimer

In this line of research I am interested in understanding the actual problem the brain faces: the control of tendon-driven limbs.

If you do not like, prefer, or use tendon-driven systems—kudos to you. Check your e-mail, I won't mind ;)

But if you are interested in understanding the structure-function relationships in biological or engineered tendon-driven systems…listen on.

In fact….

The cool problem here is that we have no say in the neuromechanical structure of the systems…. and we have to reverse engineer it.

Fundamental premise:
Newton and Darwin are *unforgiving*

Mechanics describes the
undeniable physical reality organisms must face.

Evolutionary biology is the response to that reality. Organisms are a result of successful brain-body co-evolution.

What can we learn from the human hand?

Where is one to begin?

From <u>The Help</u> by Kathryn Stockett, a novel about life in the ‘60s:

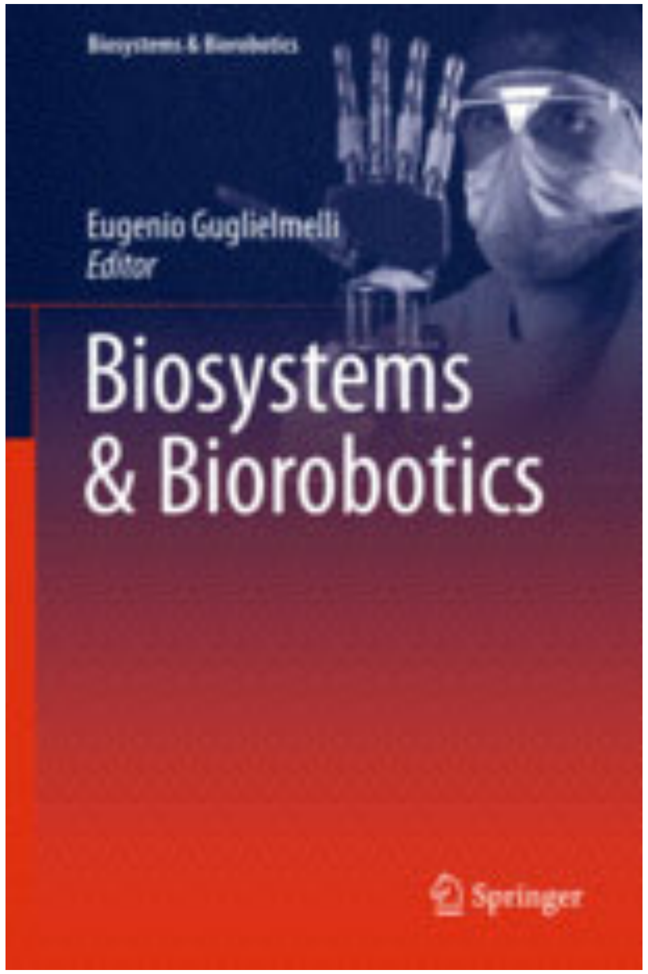
…get an entry-level job... When you’re not making mimeographs ... look around, Don’t waste your time on the obvious things. ***Write about what disturbs you, particularly if it bothers no one else.***

Some mechanics-based examples of things that have been disturbing me

Is the human hand really as neuromechanically redundant, robust and versatile as we say?

How does the brain interact with the spinal cord to produce dexterity?

Upcoming Springer-UK book 2015



Francisco J. Valero-Cuevas

Neuromechanics: The problem the brain solves

Neural control of tendon-driven limbs

Biosystems & Biorobotics series

Redundancy as the central problem of motor control

Popular View:

We have many more muscles (i.e., control degrees of freedom) than necessary.

This allows for infinite solutions.

Therefore the CNS is faced with the tough computational problem of decision-making (or optimization).

But this is paradoxical with evolutionary biology and clinical reality

That is,

For decades, neuroscientists and biomechanists have been exploring how to effectively choose specific muscle actions from a set of infinite choices.

but...

If we are so redundant:

Which muscle would you like to donate?

Why do people seek clinical treatment for dysfunction even after mild pathology?

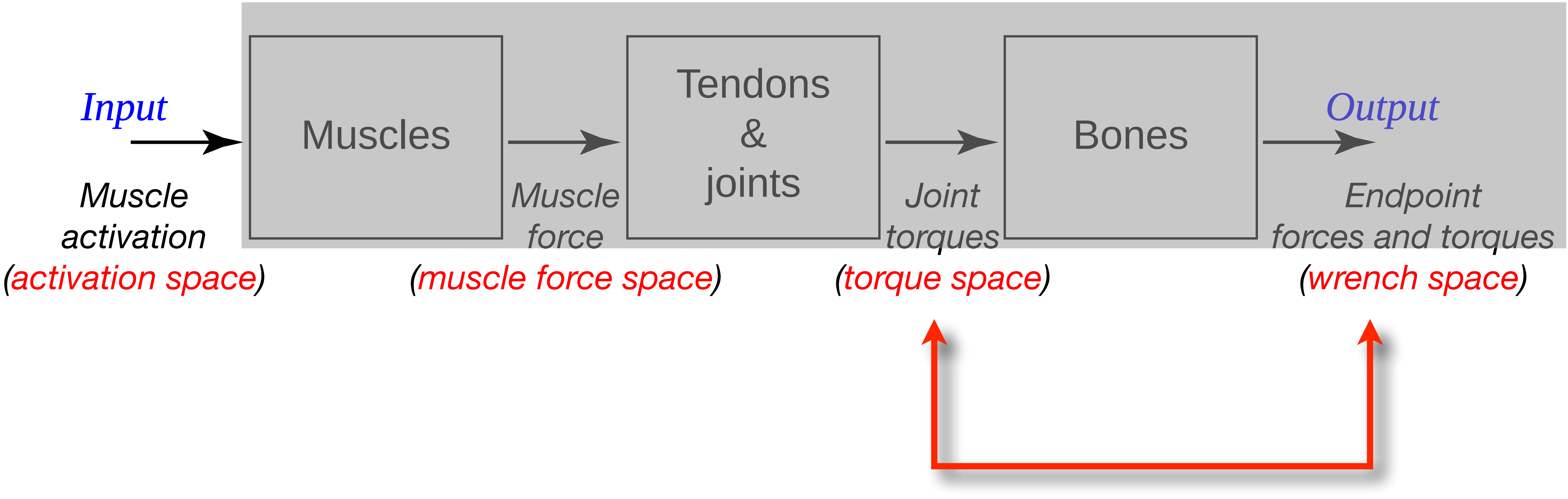
Why would we evolve, encode, grow, maintain, repair, control, etc. so many muscles?

A (heretical) proposal

- Musculature is not “redundant” for natural behavior.
- i.e., only by adding “many” muscles can you remain functional and robust as you add realistic functional constraints.
- We have barely enough muscles for ecological function (neuroethology).

The musculo-skeletal system “filters” the propagation of neural commands, and defines **feasible** inputs and outputs

Block diagram of transformations in a forward limb model



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

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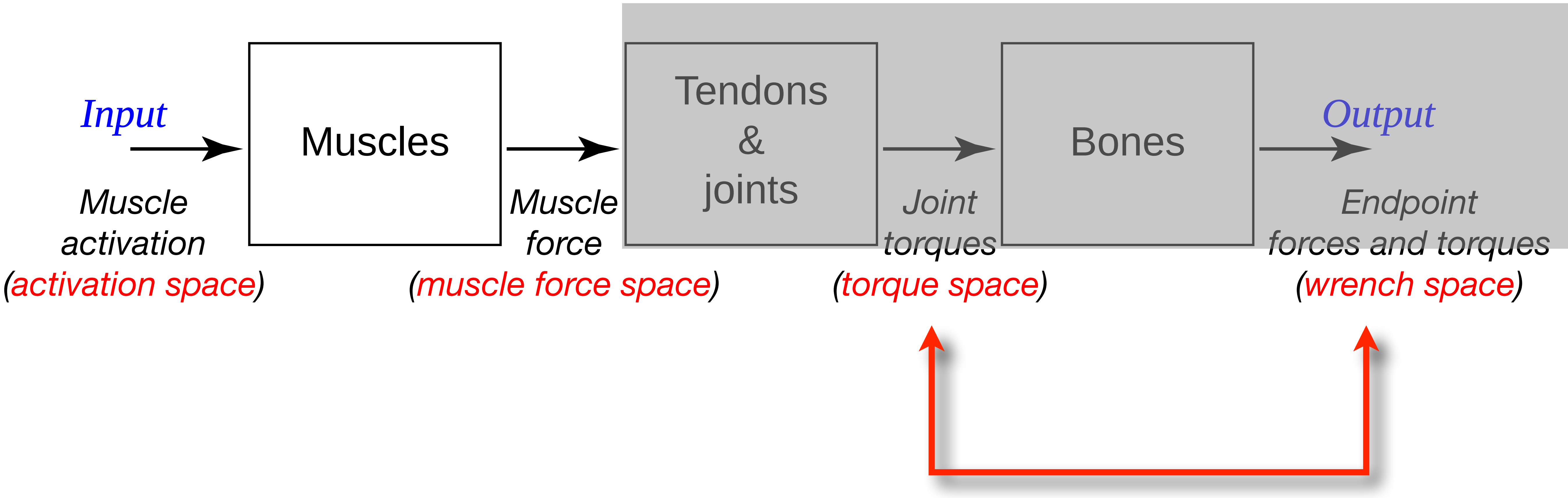

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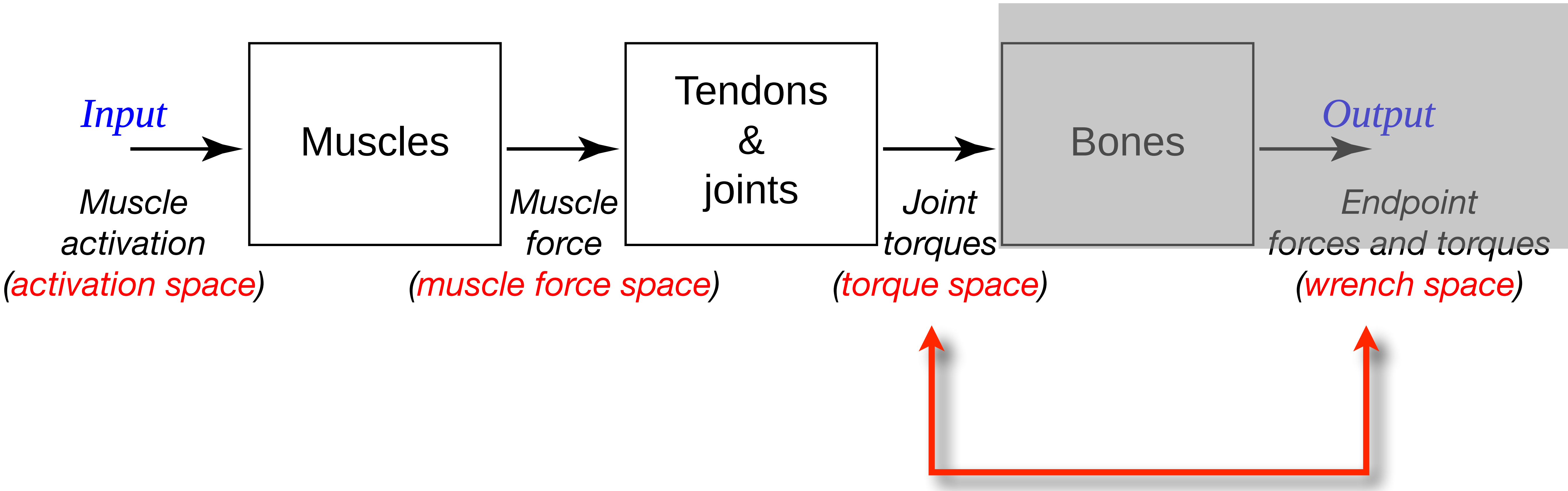

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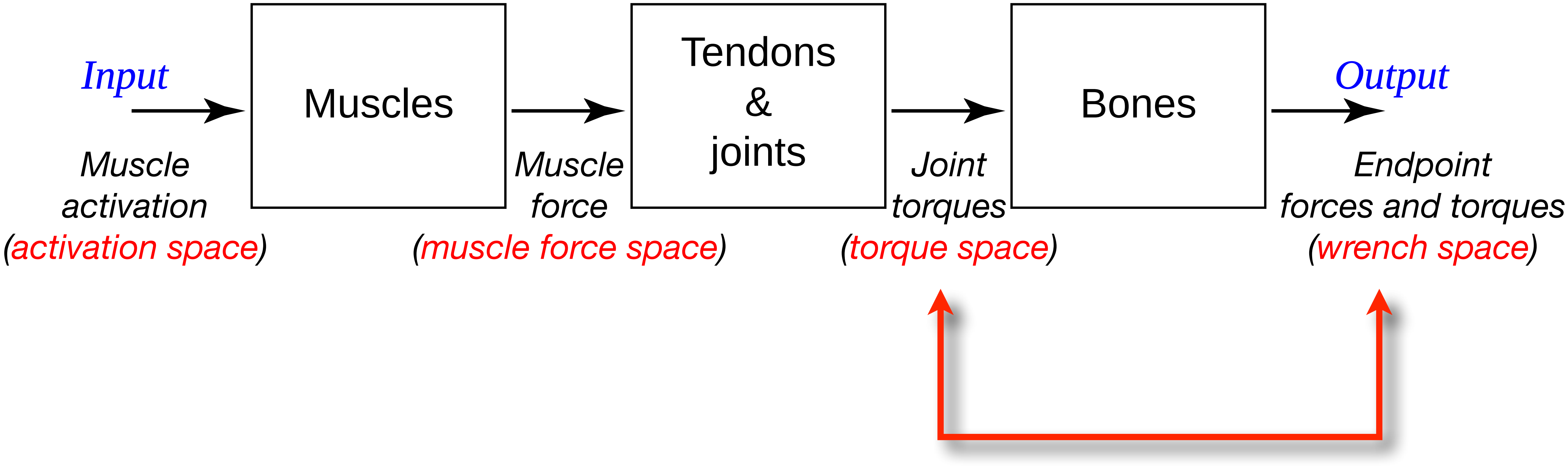

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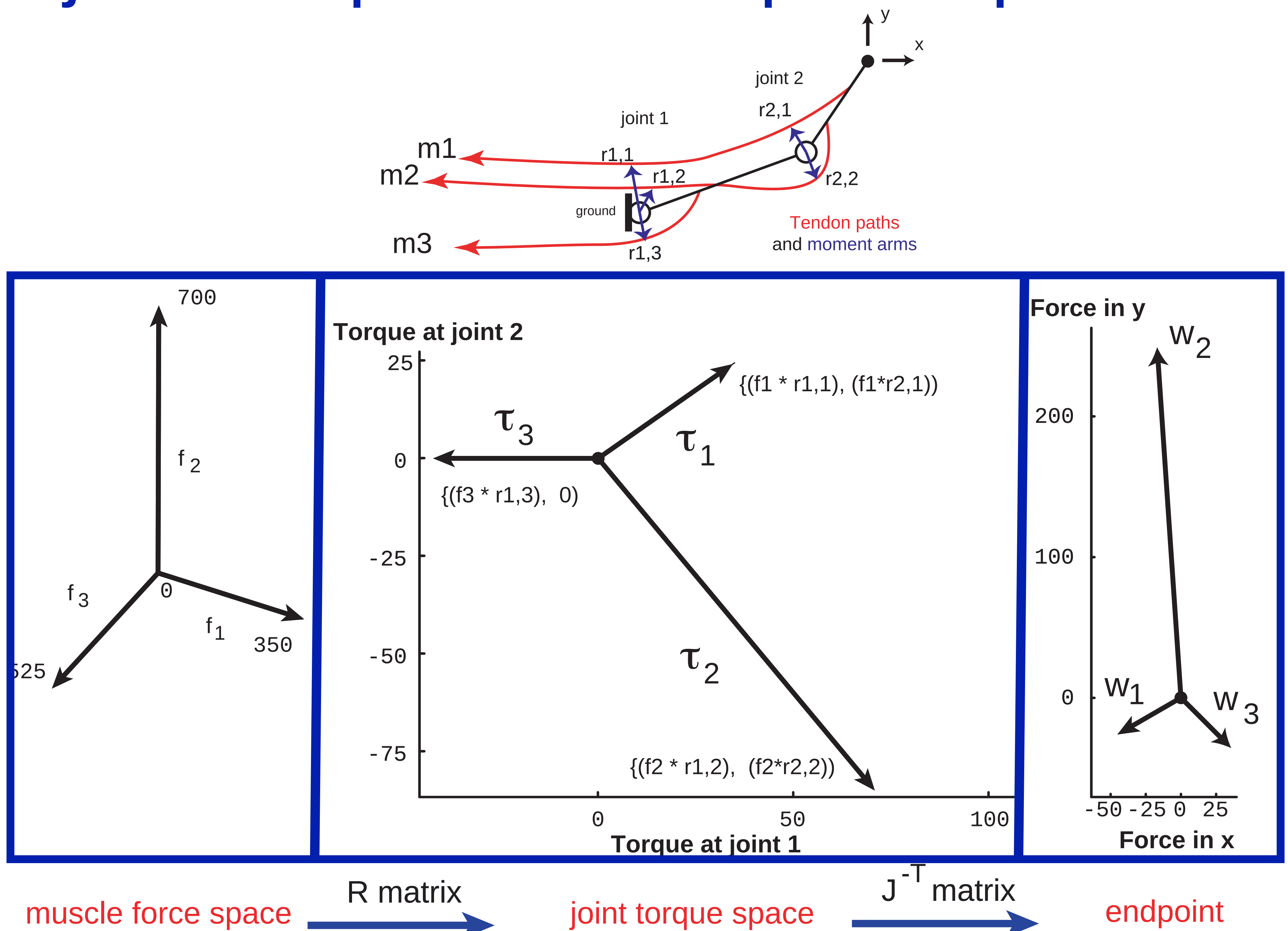
Muscle actions: from tendon routing to joint torque and endpoint spaces



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

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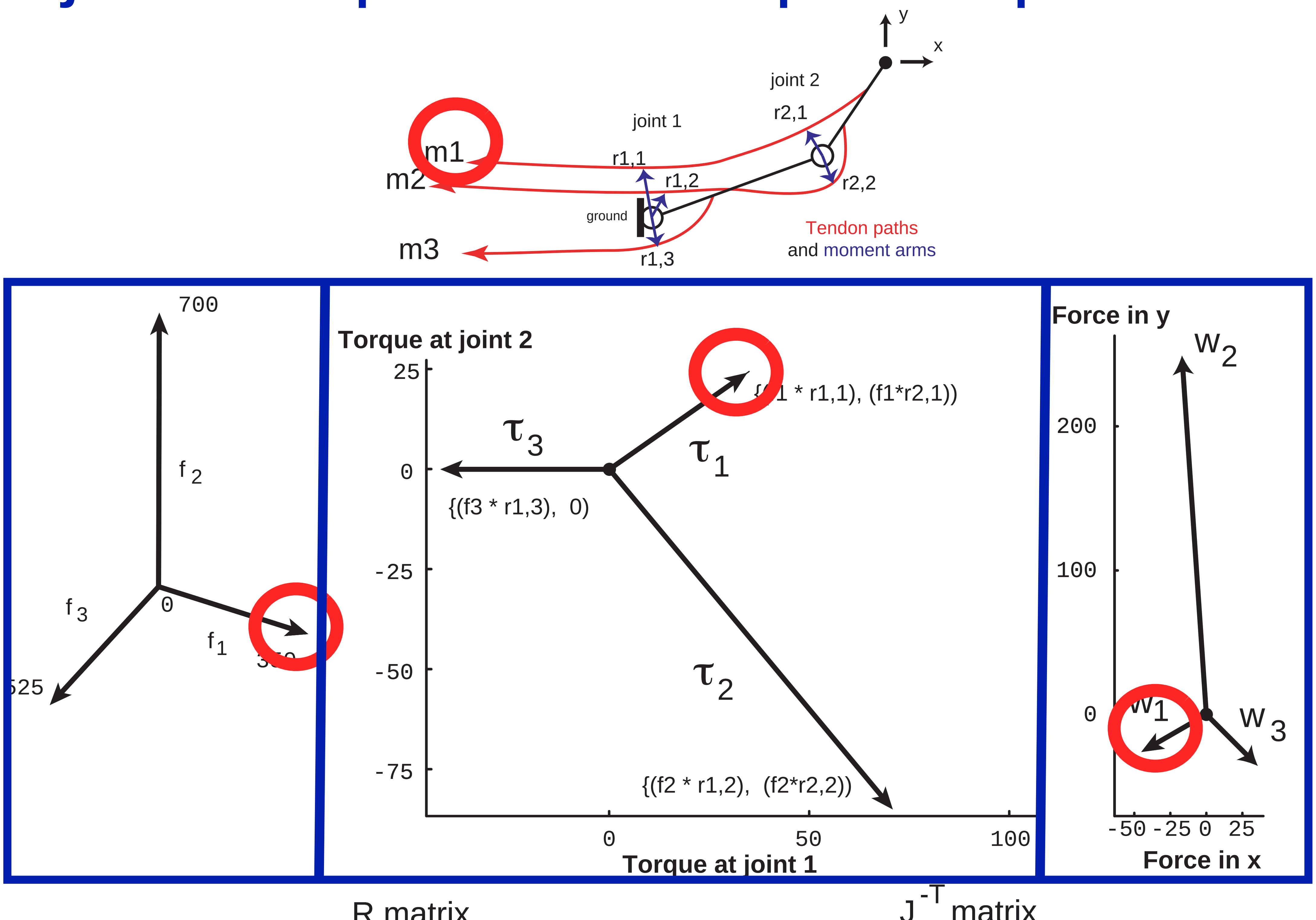

muscle force space (N) → joint torque space (N-m) → endpoint wrench space (forces in N)

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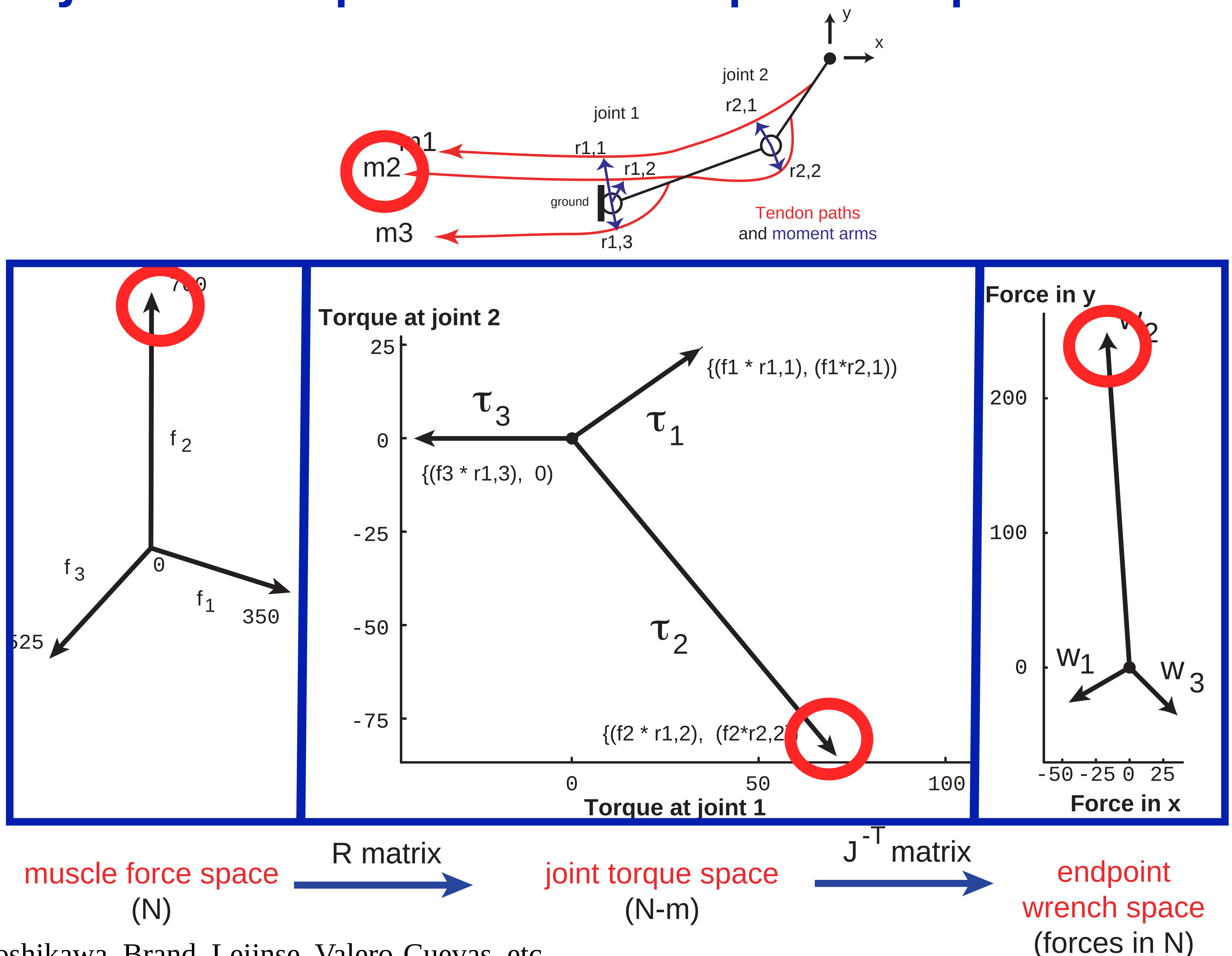

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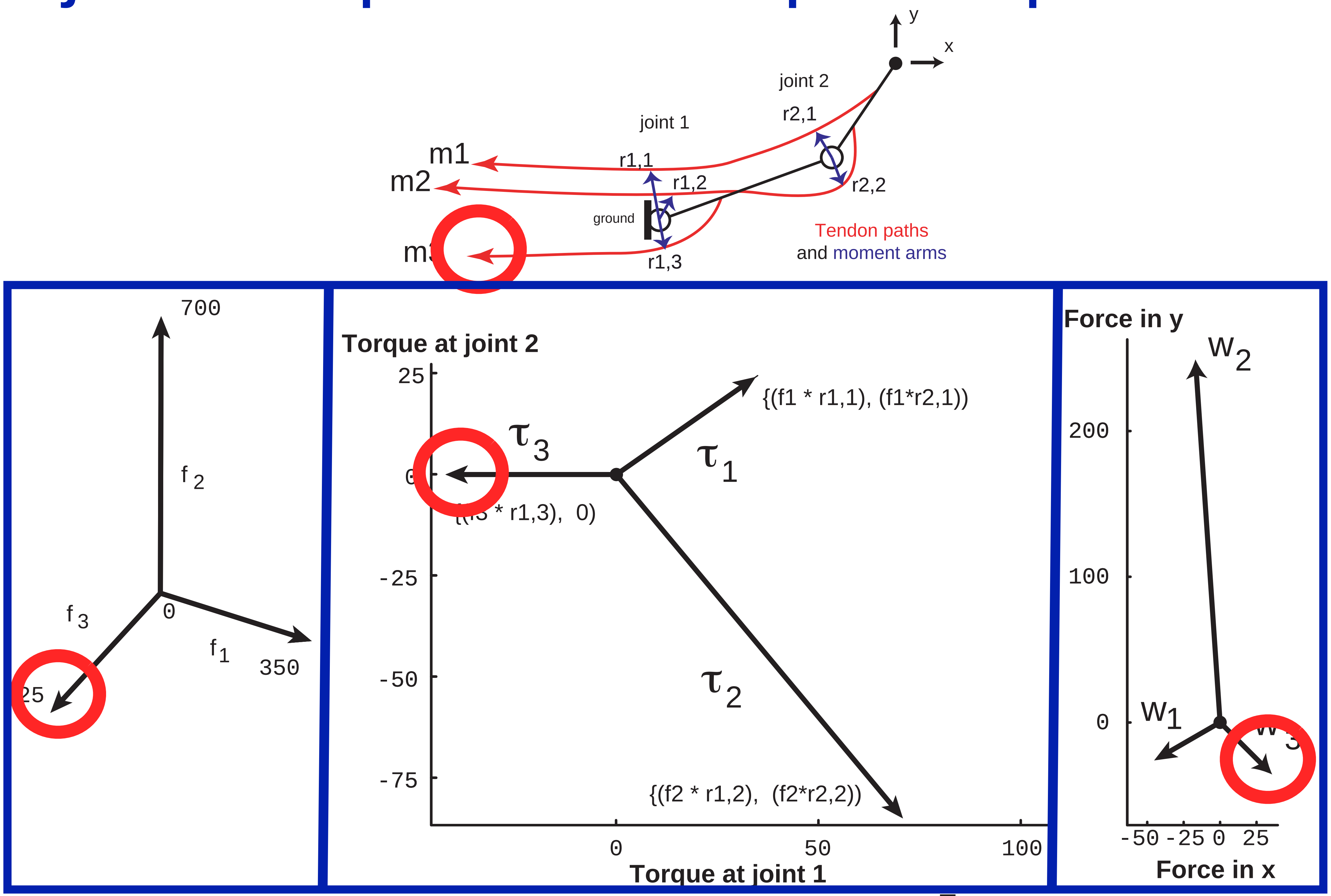

muscle force space (N) → R matrix → joint torque space (N-m) → J^{-T} matrix → endpoint wrench space (forces in N)

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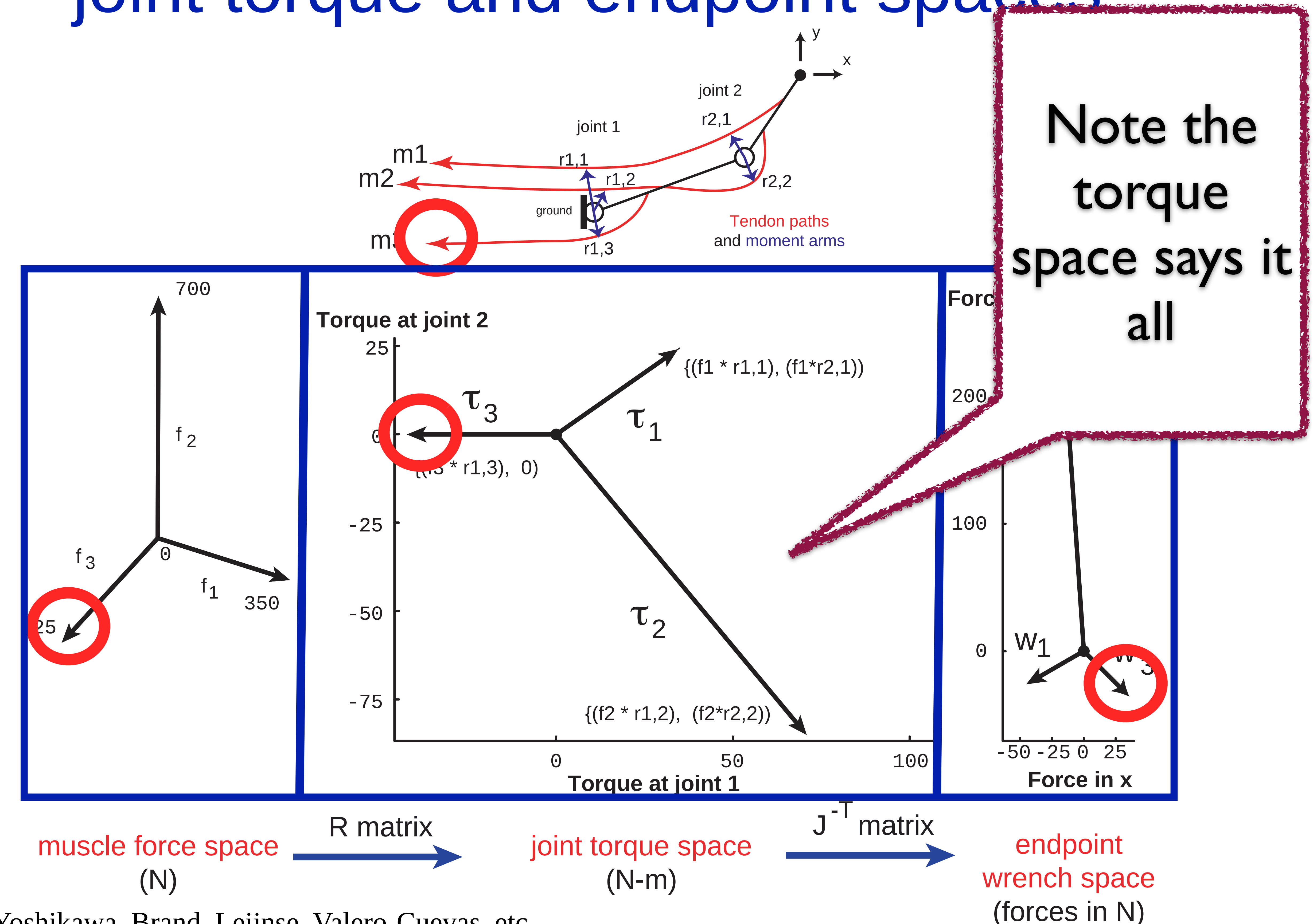
Muscle actions: from tendon routing to joint torque and endpoint spaces



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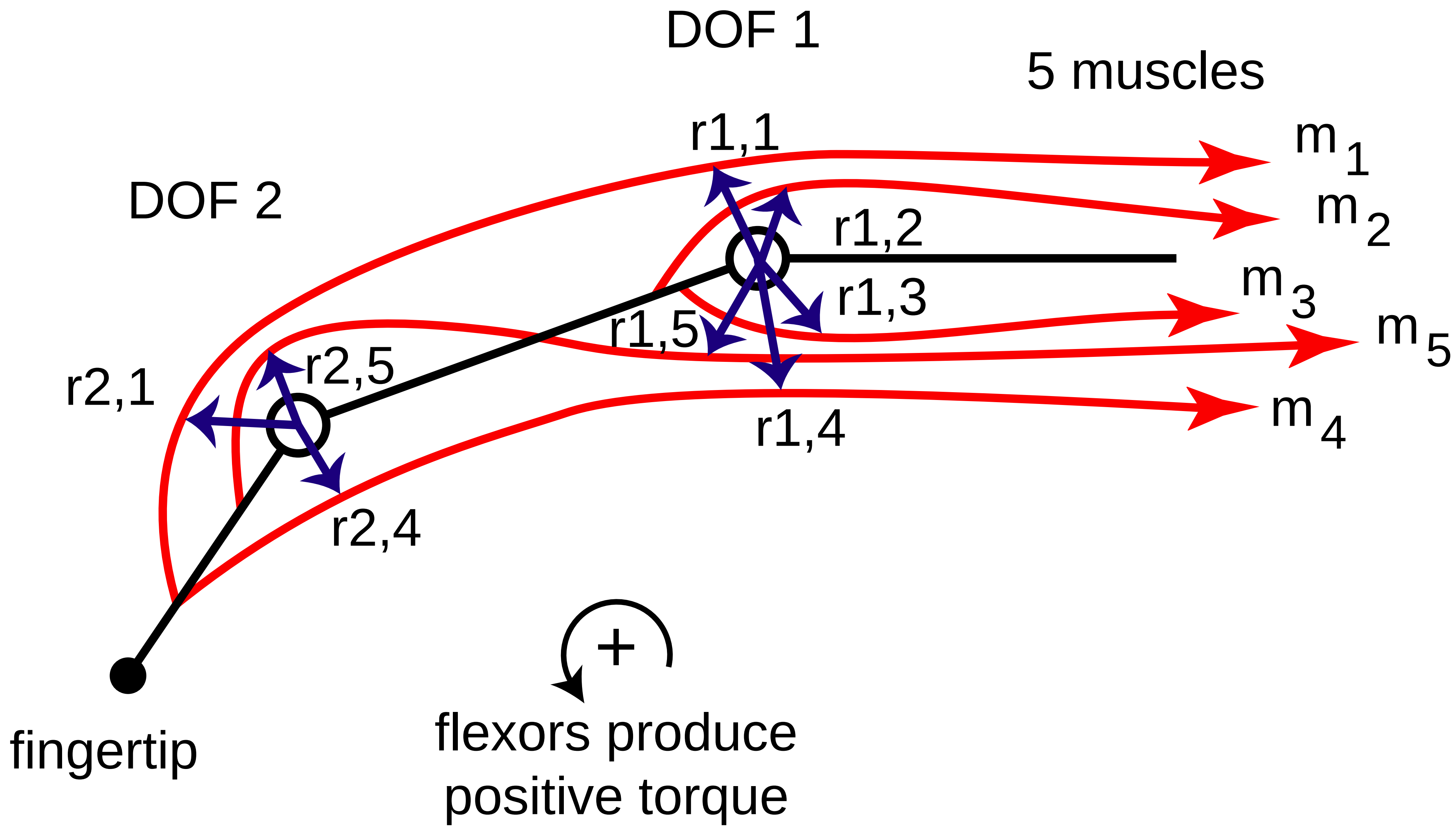
Building a feasible torque set for a “complex” limb



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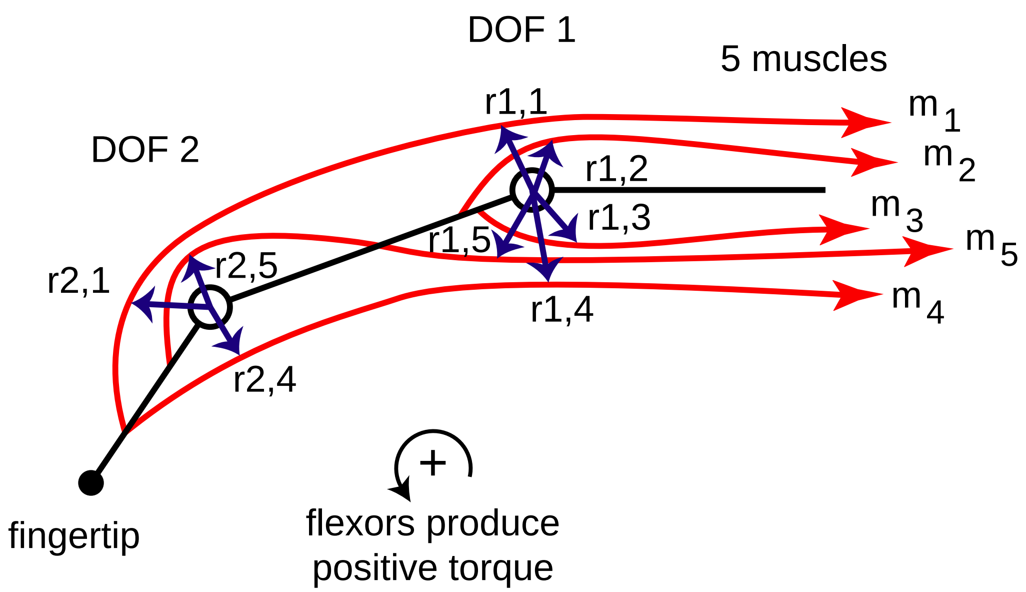

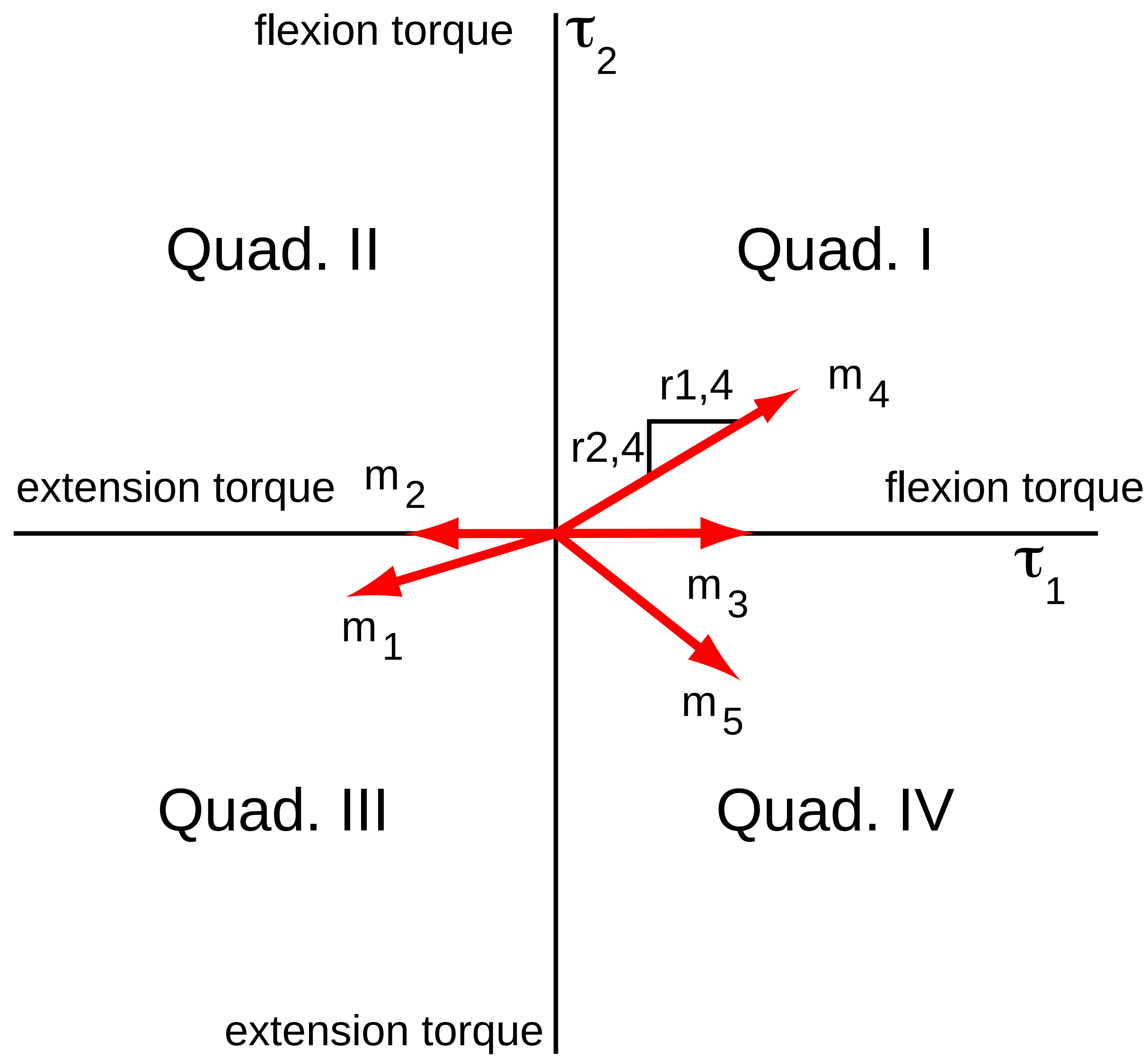

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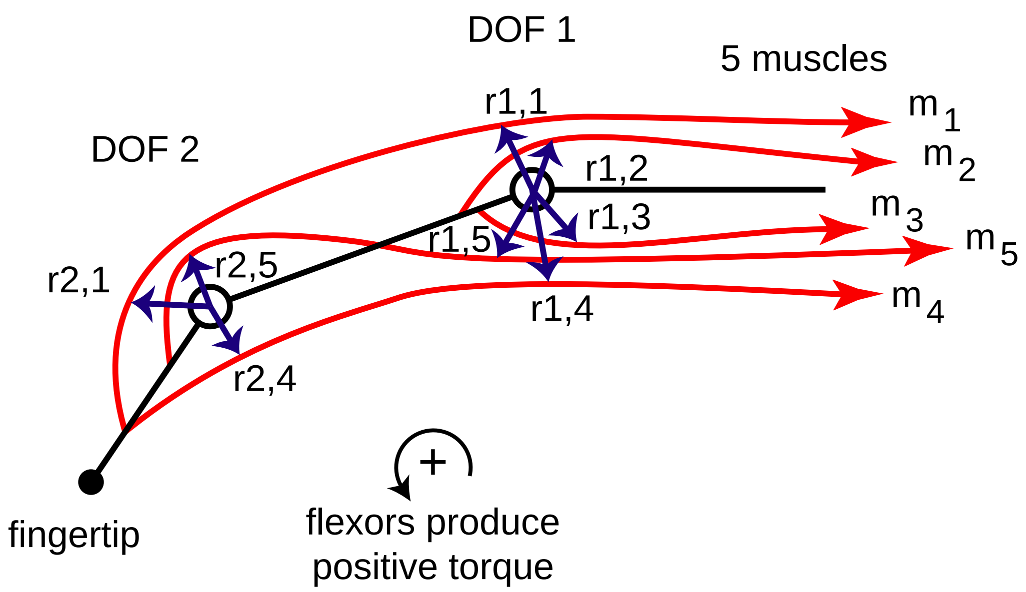

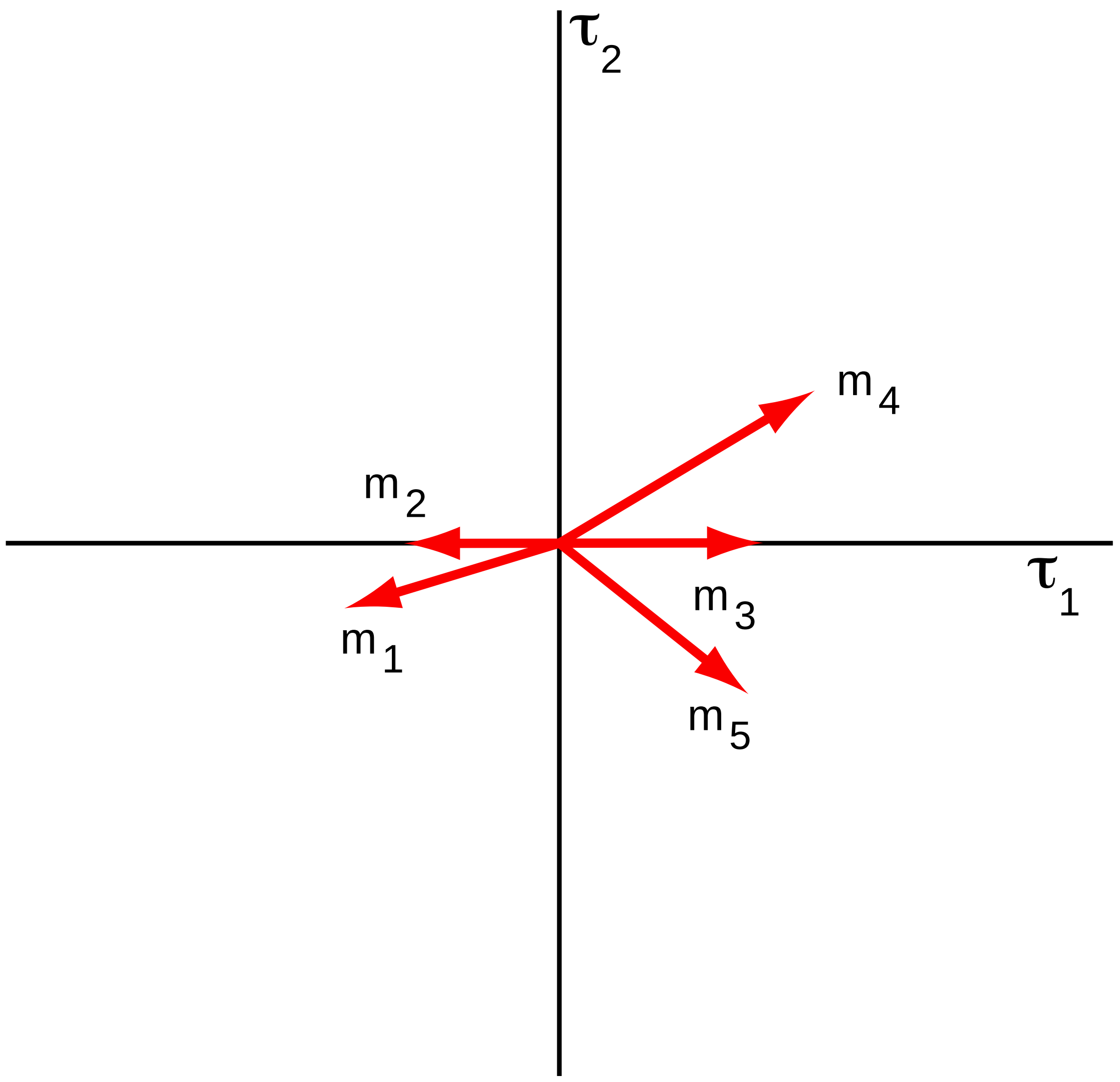

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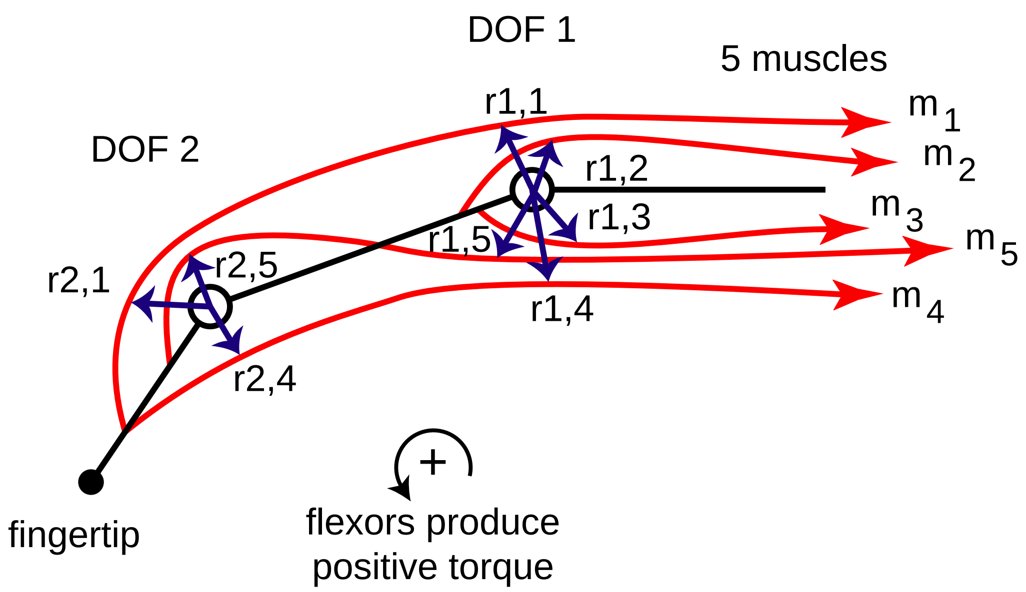

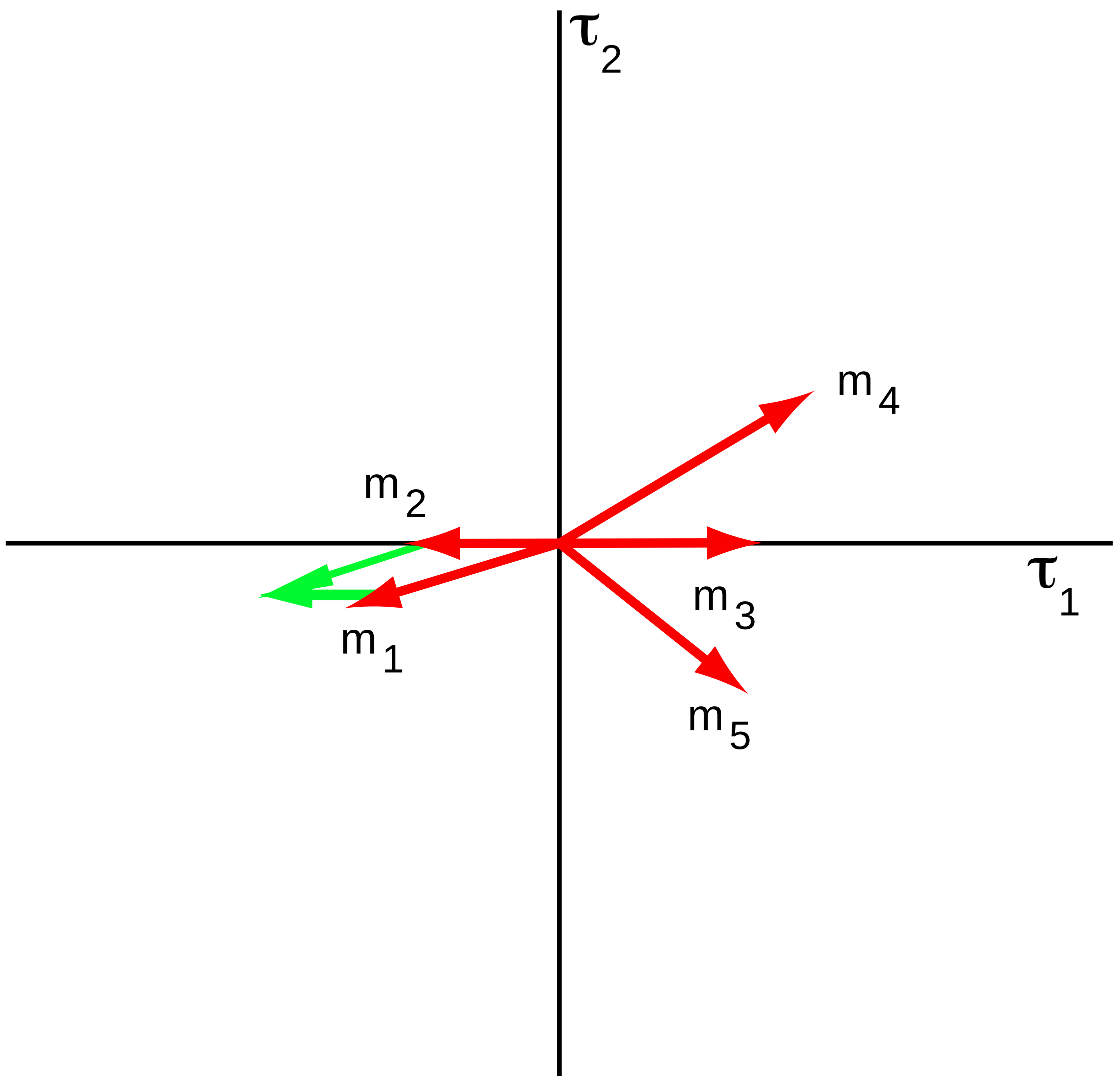

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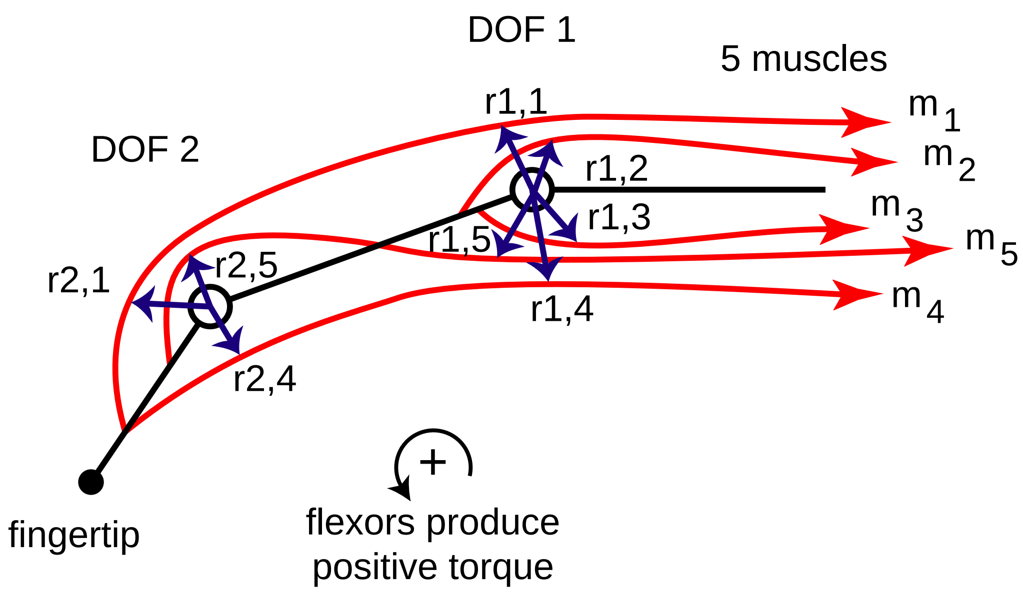

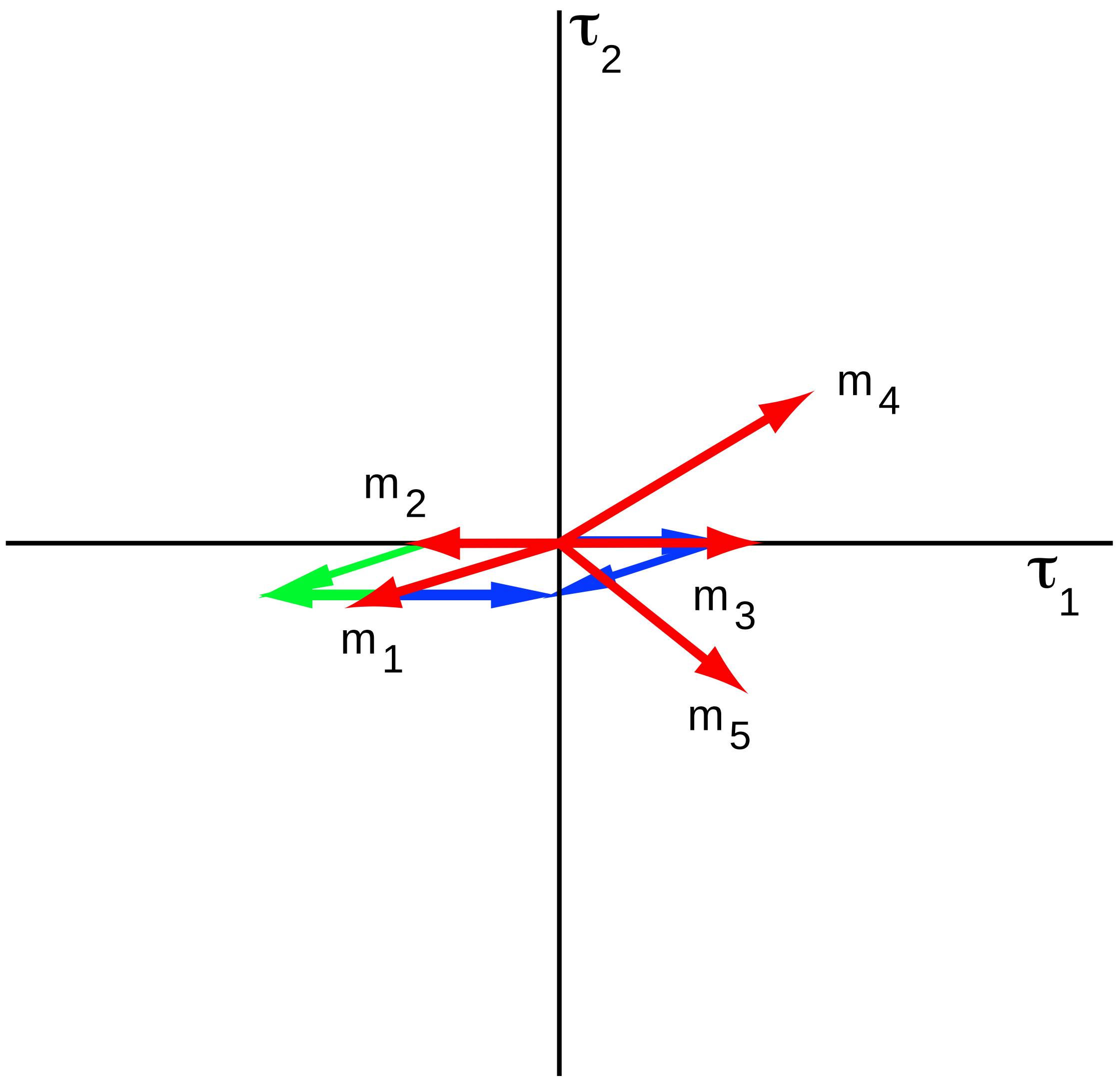

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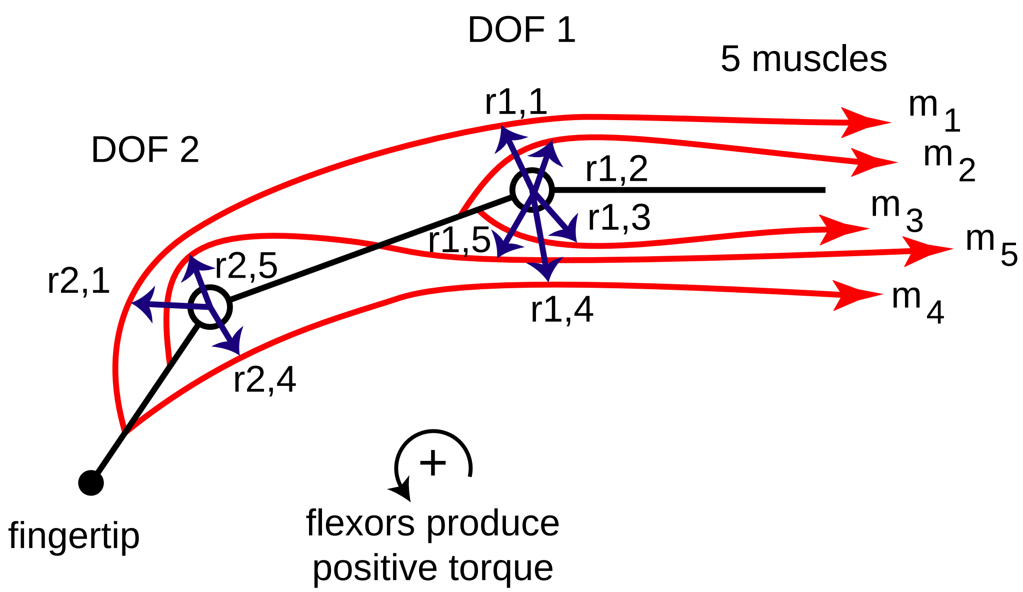

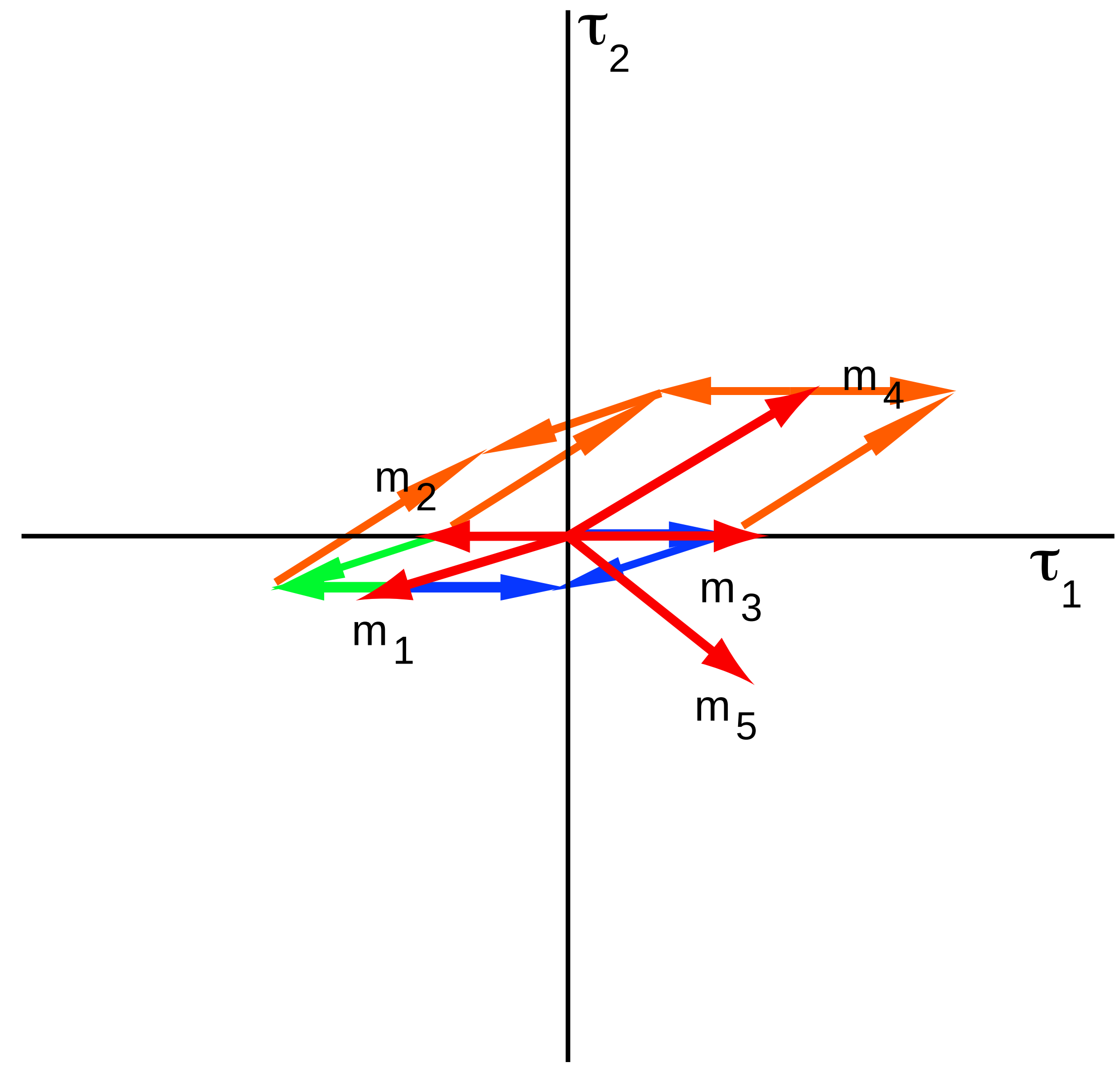

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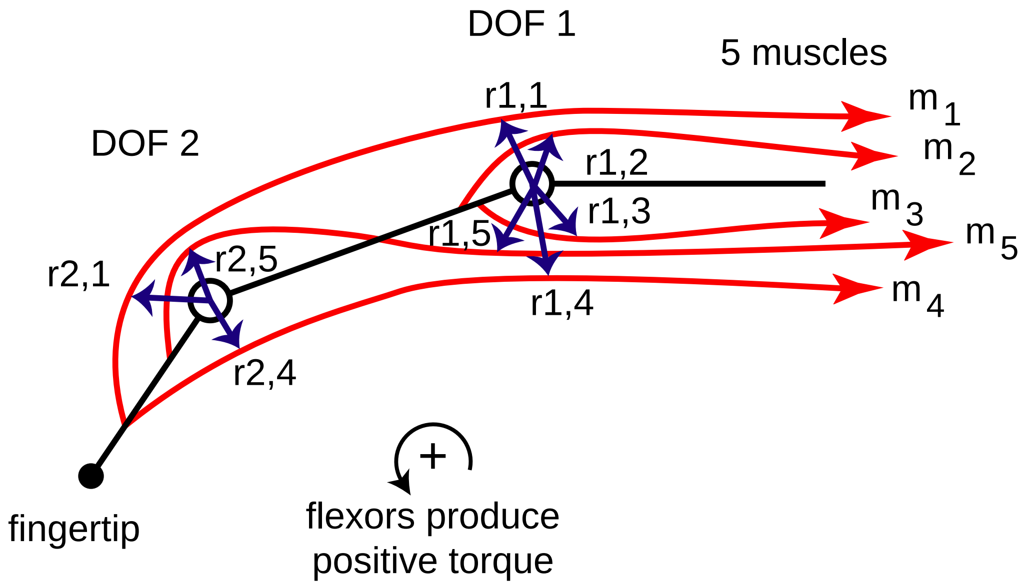

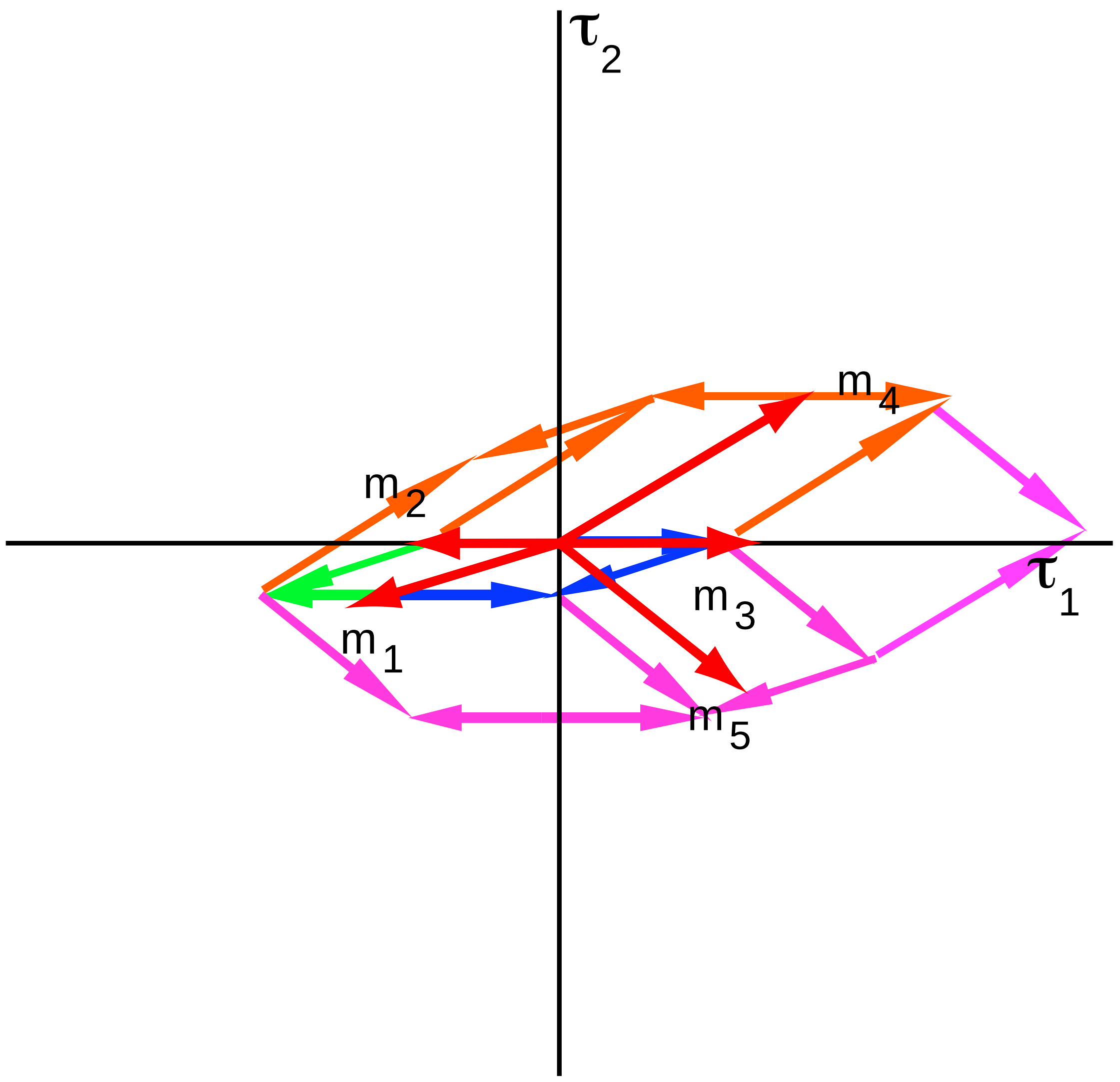

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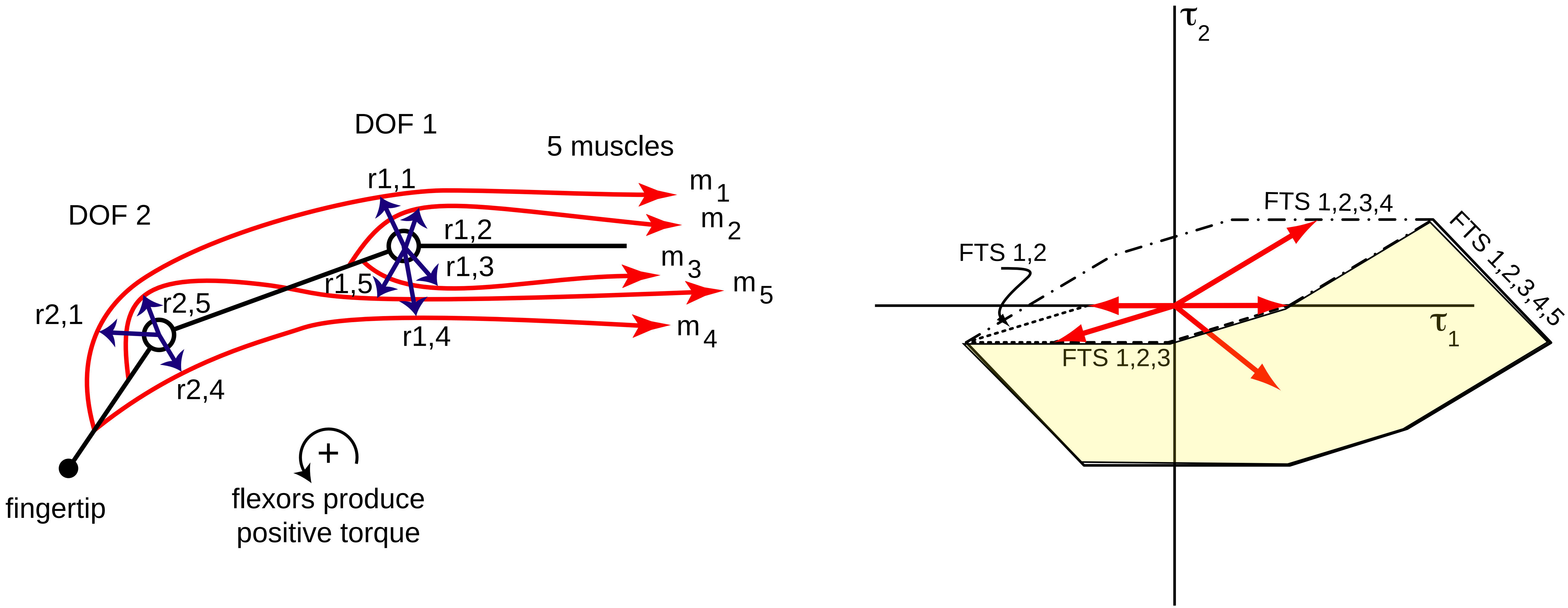
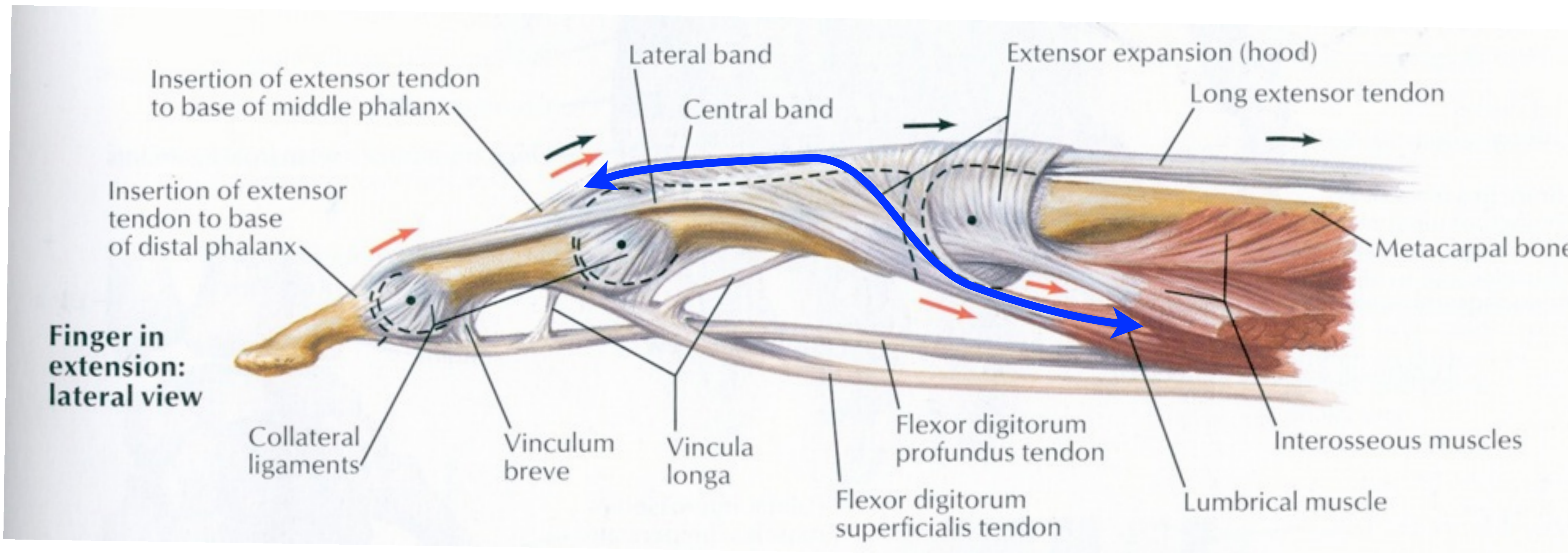
Interesting fact: “Cross-over” tendons



m5: a crazy tendon to put in a robotic system...

But it exists: The extensor mechanism system of the human fingers



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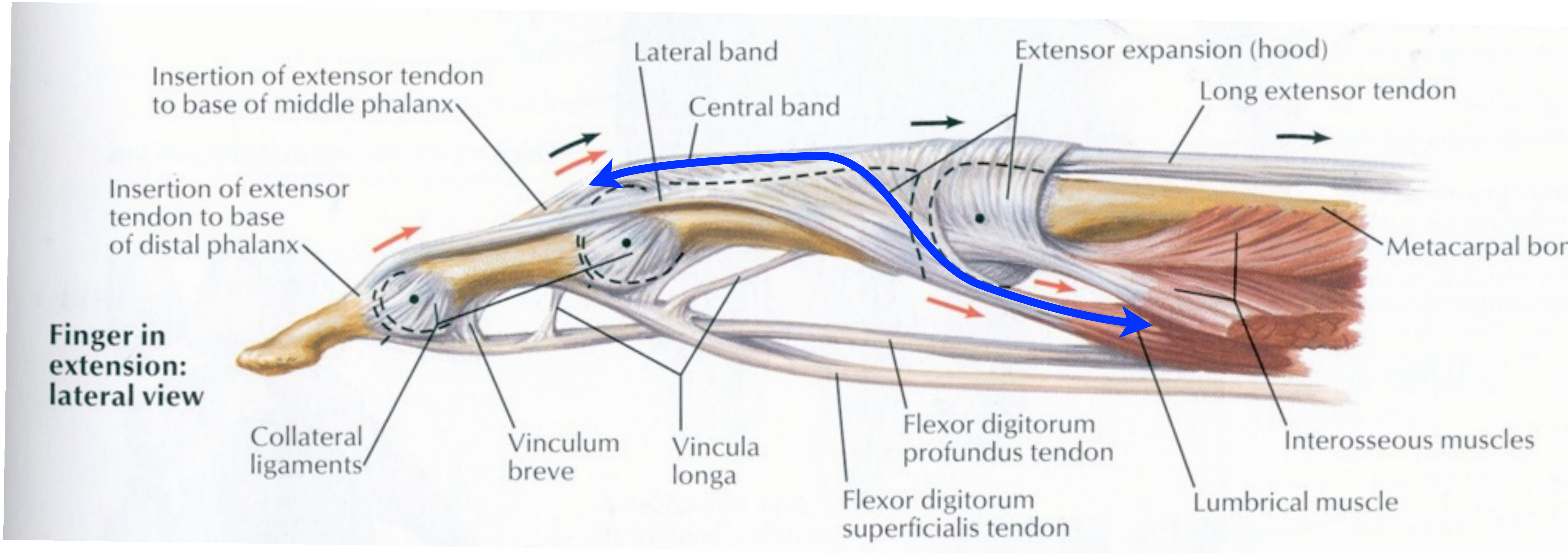
This forces us to (re)evaluate what is "easy" or "hard" to control, or what is a "simple" or "complex" hardware



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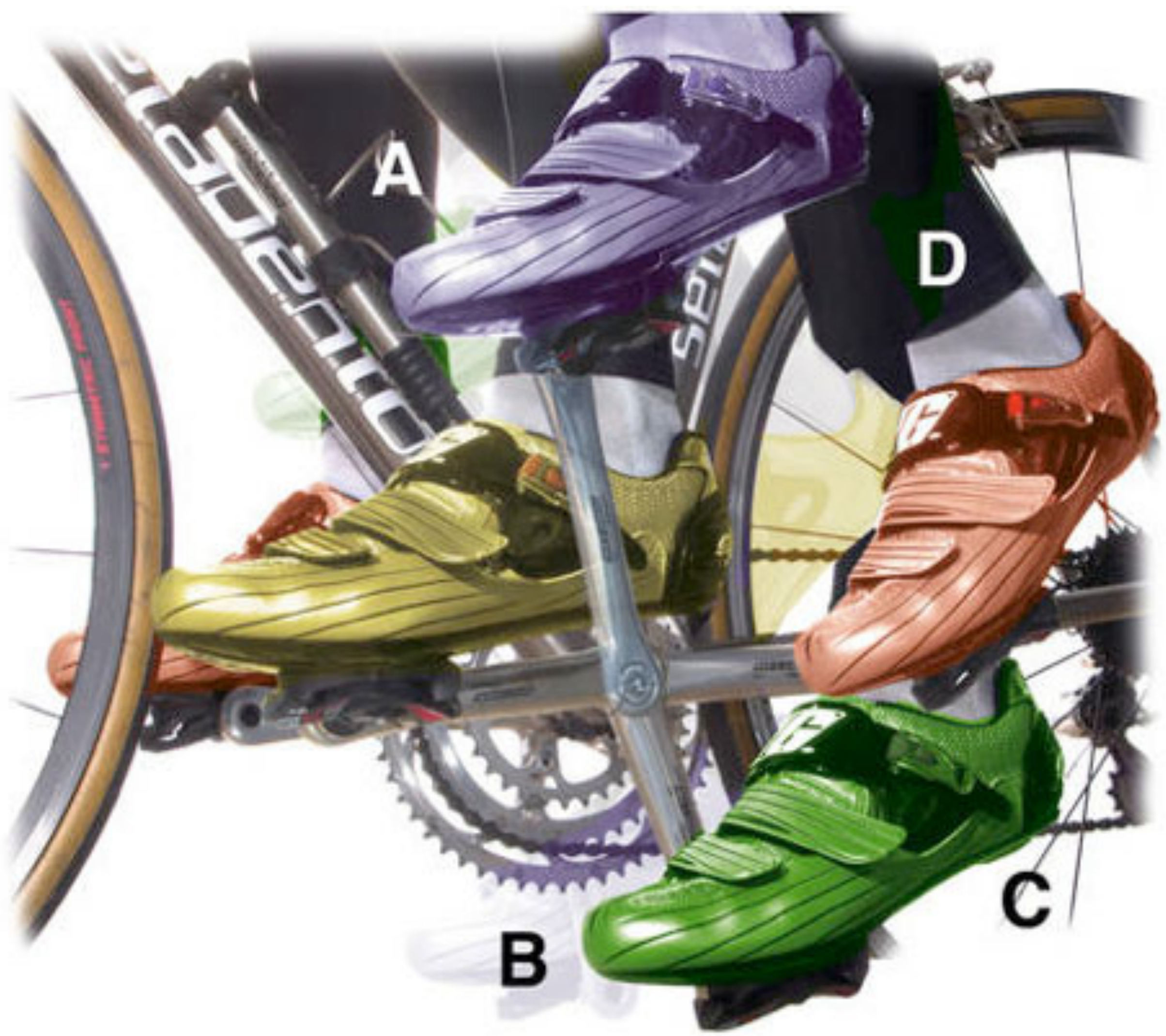
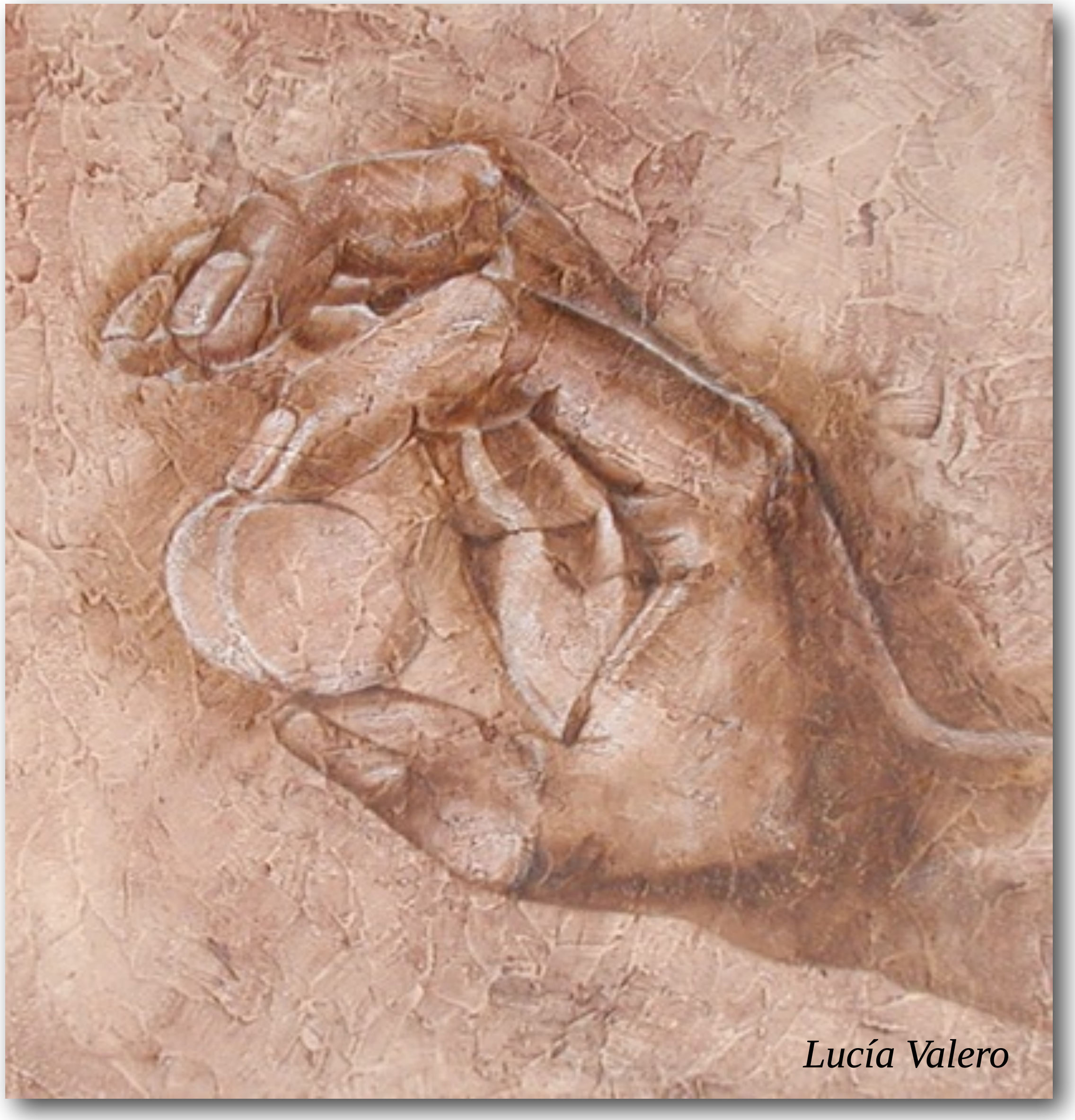
One analytical starting point: A working definition of "versatility"

Simply put: the ability to produce end-point force in every direction—i.e., controllability.

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





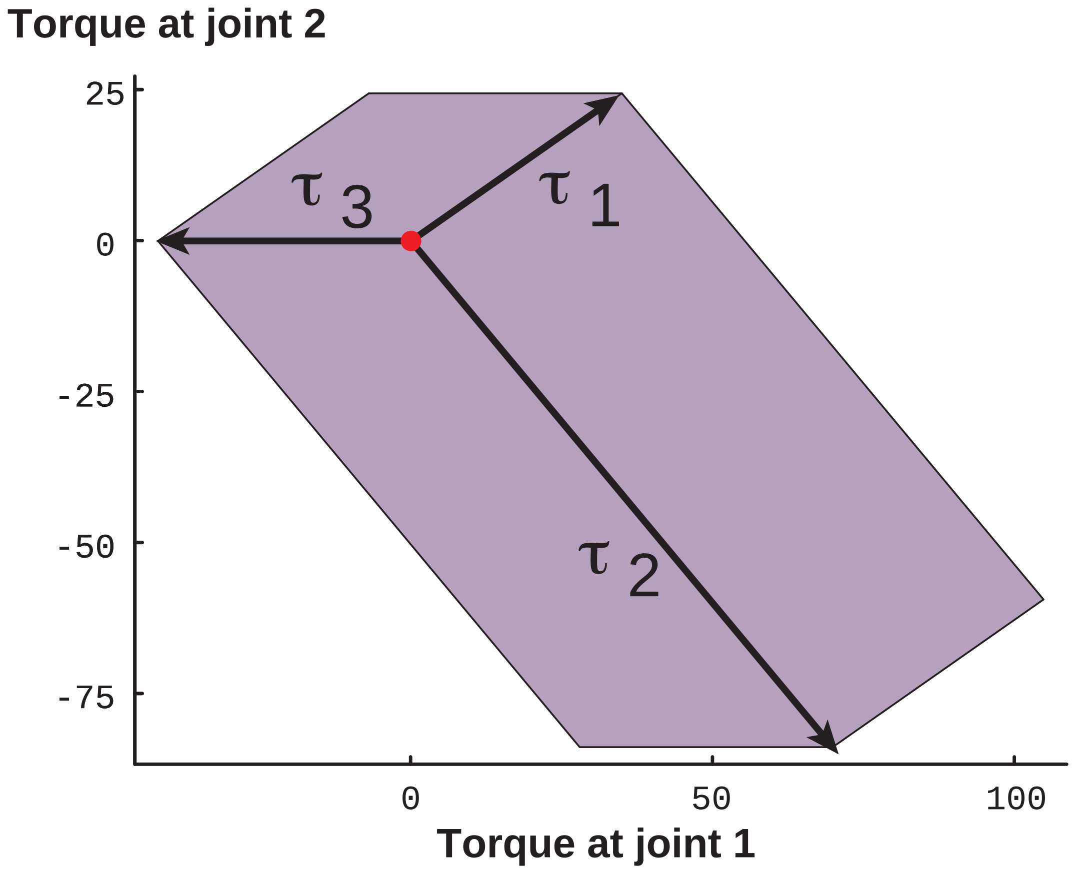
Valero-Cuevas. A mathematical approach to the mechanical capabilities of limbs and fingers. 2009.

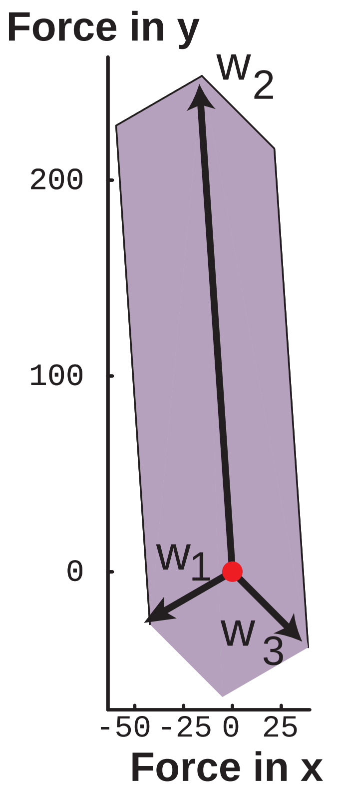
Versatility ≡ feasible torque and force sets that include the origin

convex sets remain convex under linear mapping

feasible torque set (N-m)

endpoint feasible force set (forces in N)

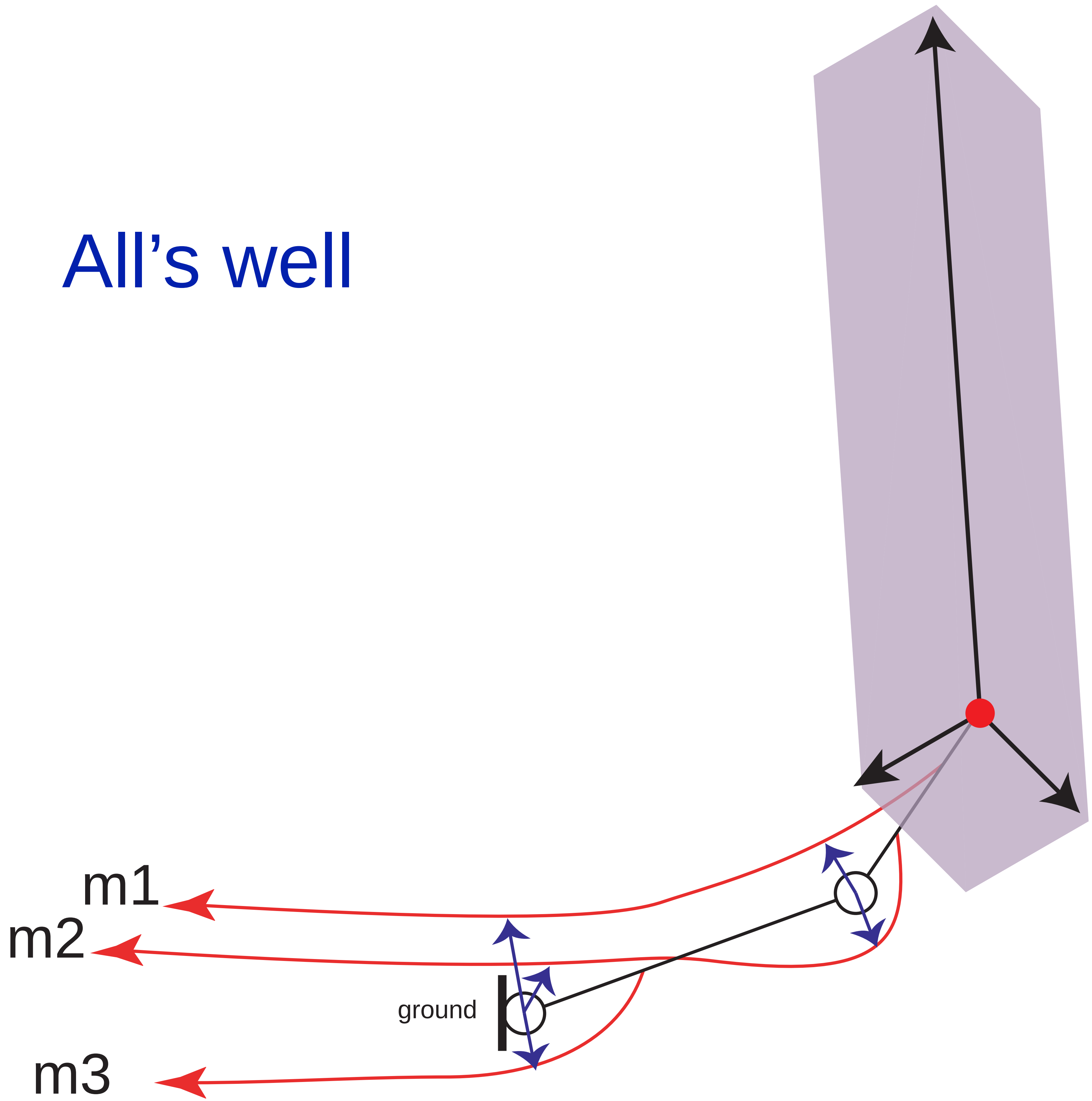




That is, producing end-point force in every Cartesian direction requires that you produce torques in every direction in "torque space"

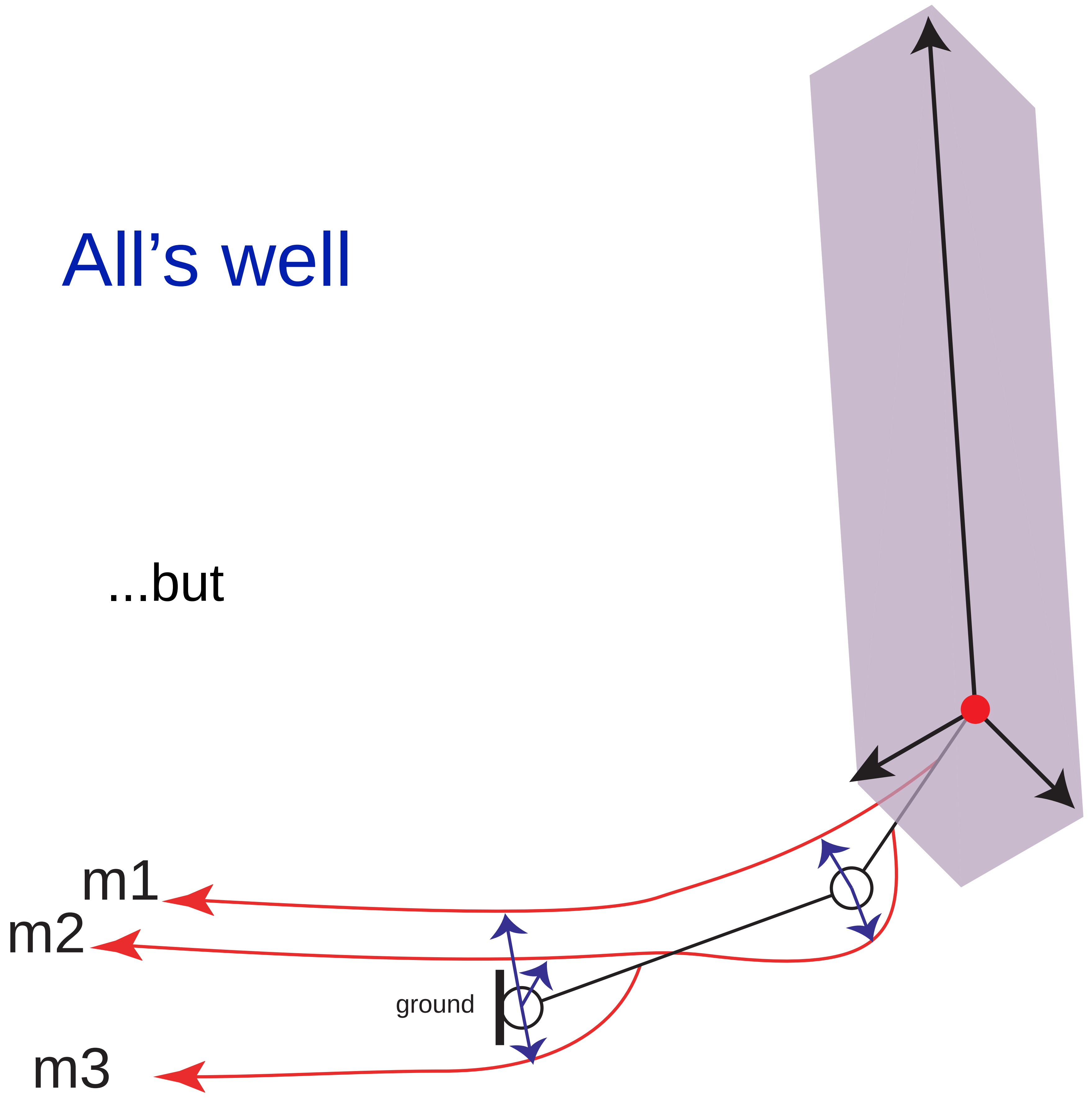
Valero-Cuevas 1998, 2005, 2009

All’s well



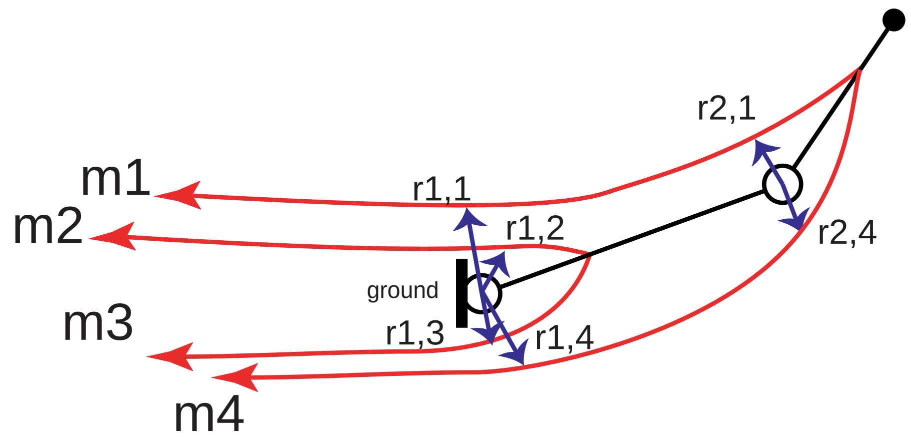
All’s well

...but

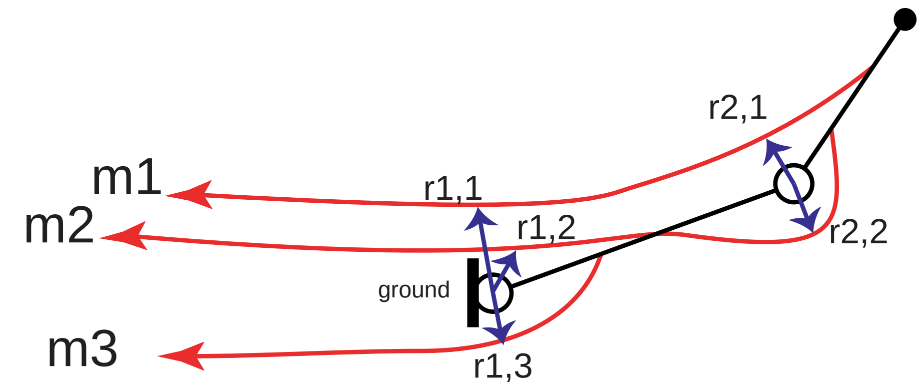


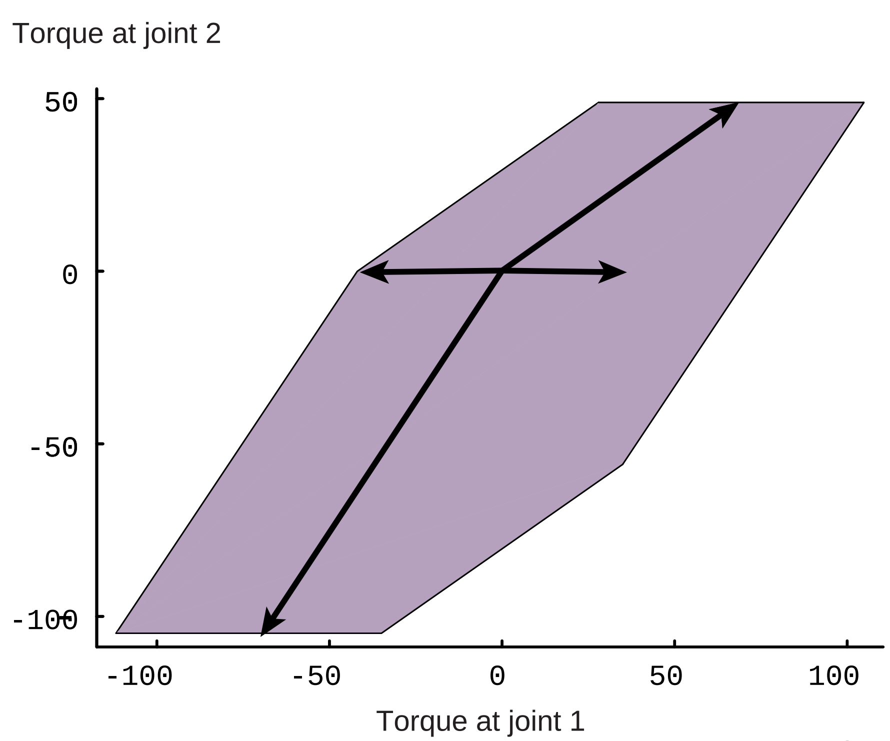
How many muscles do you need to include the origin in torque/force space?

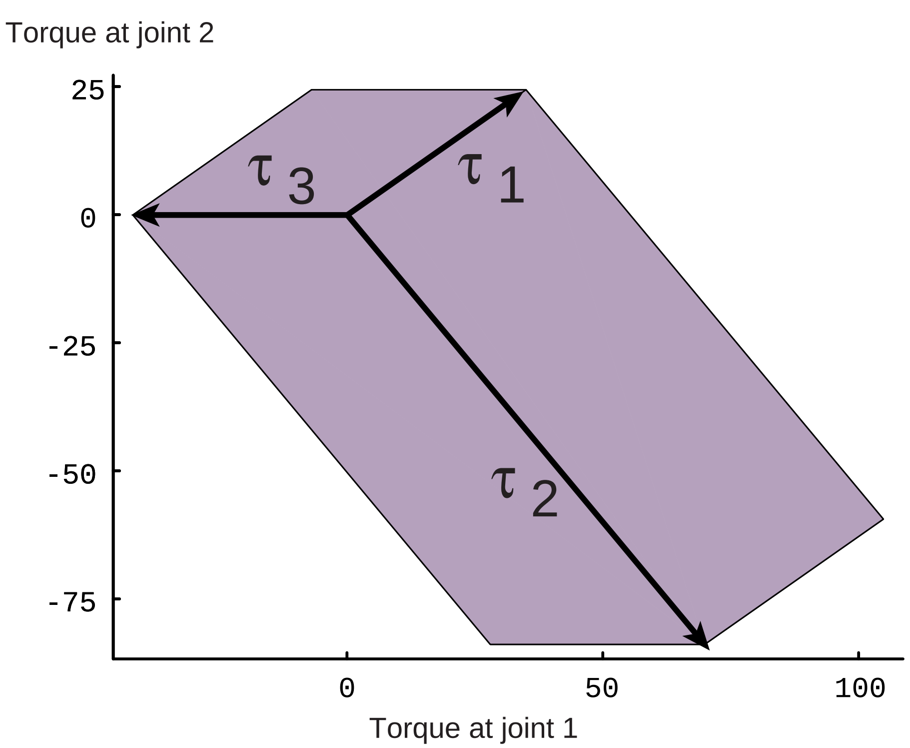
2-link limb with 4 muscles (2*N)



2-link limb with 3 muscles (N+1)







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

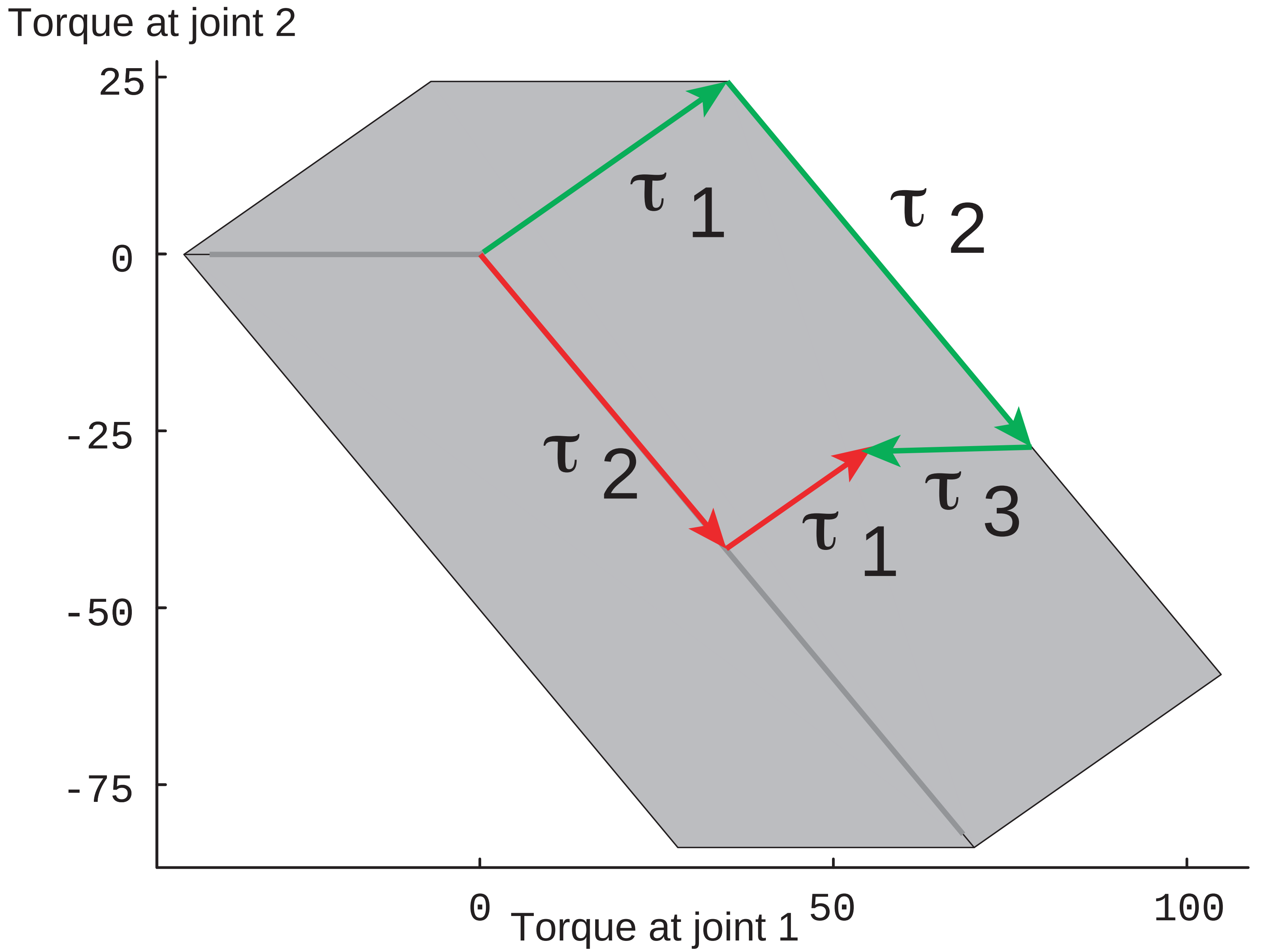
...so you need more muscles than degrees of freedom?

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!

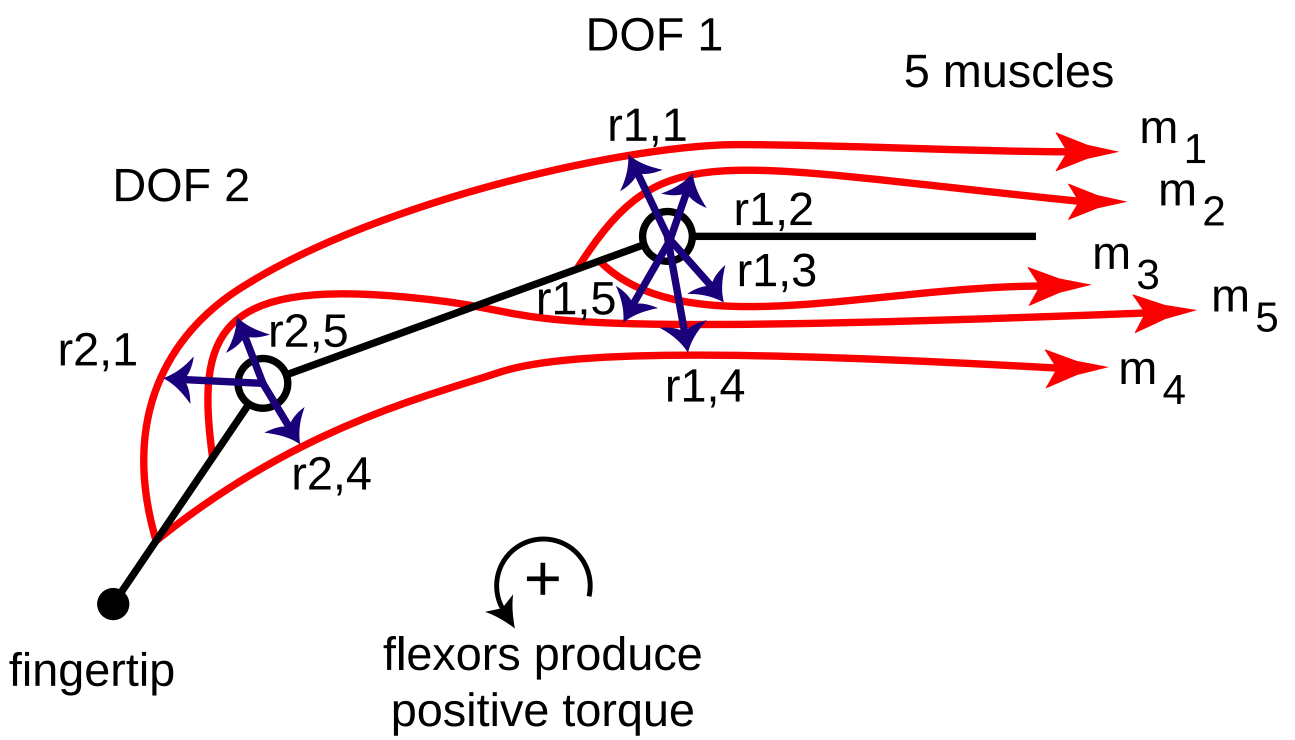


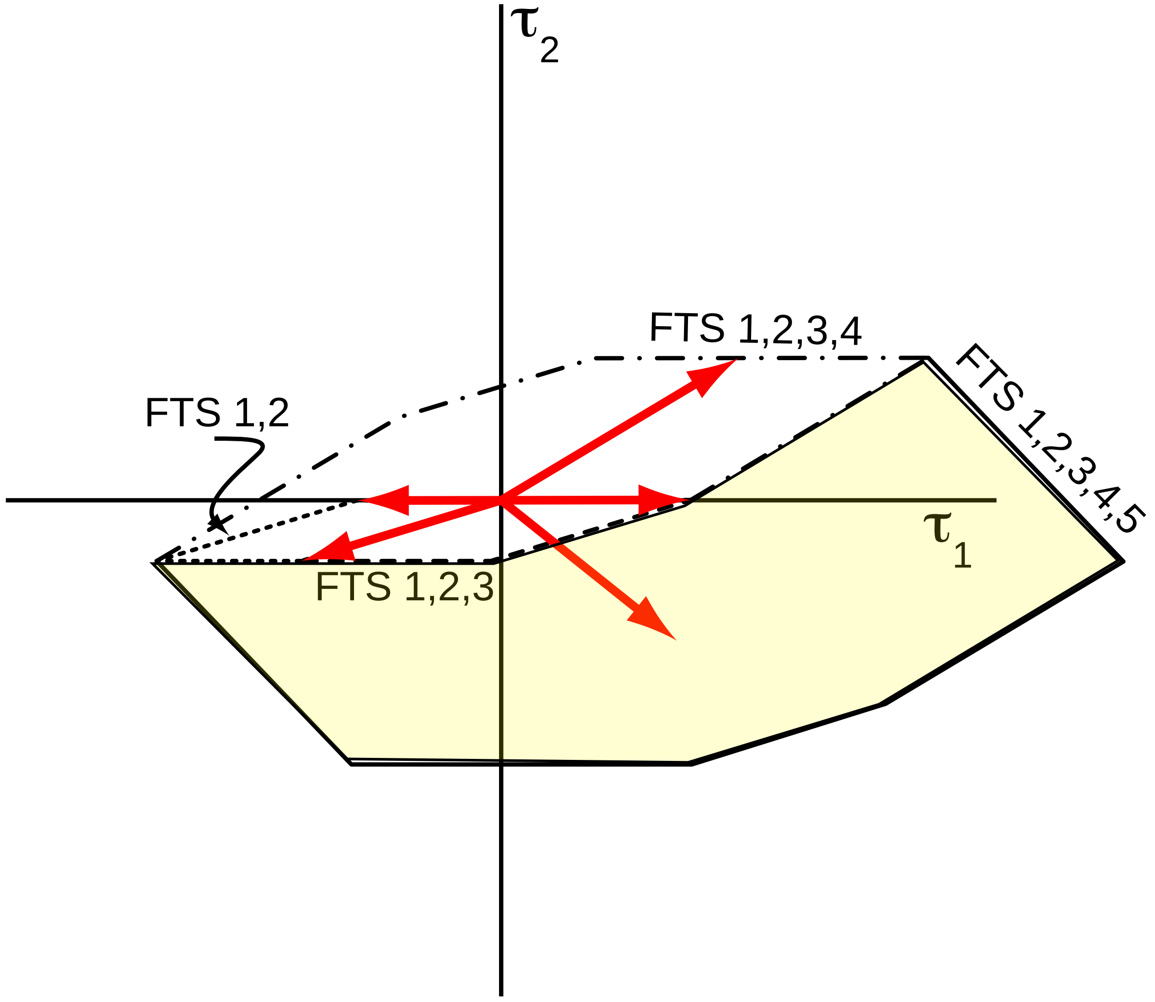
Valero-Cuevas 1998, 2005, 2009

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

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

And each tendon contributes in unique ways





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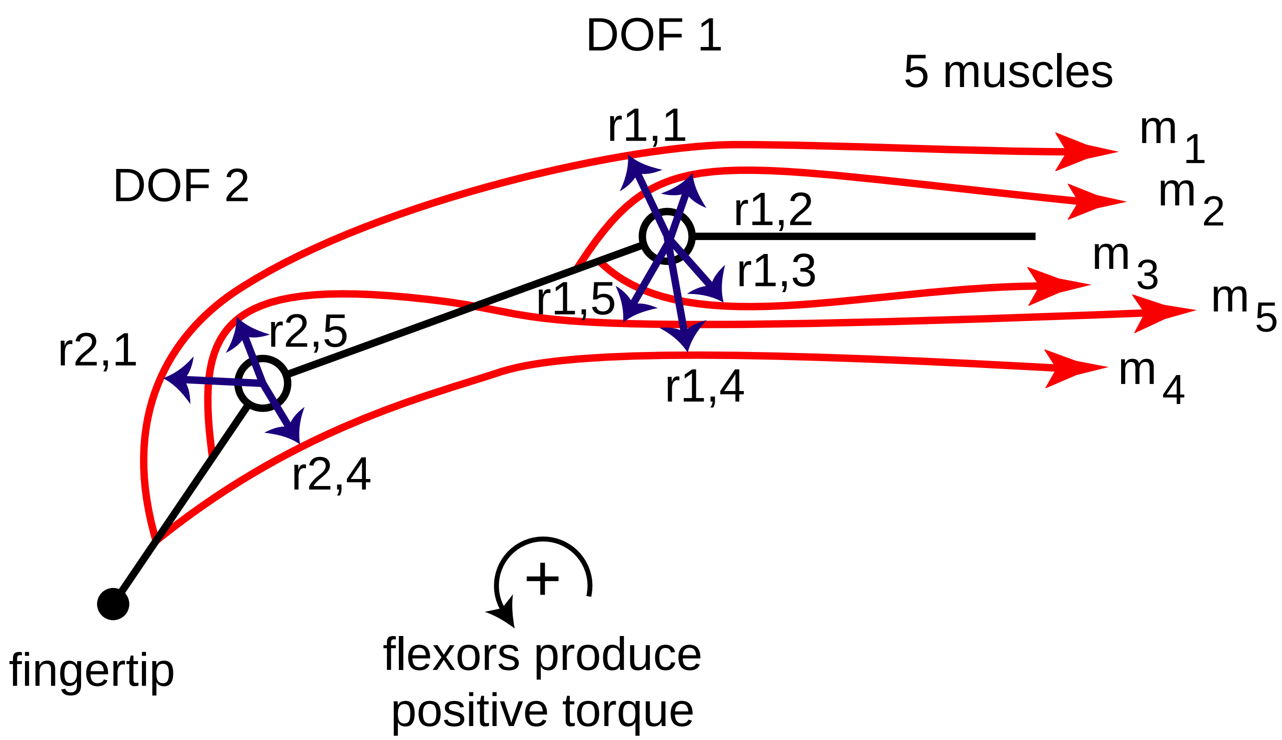
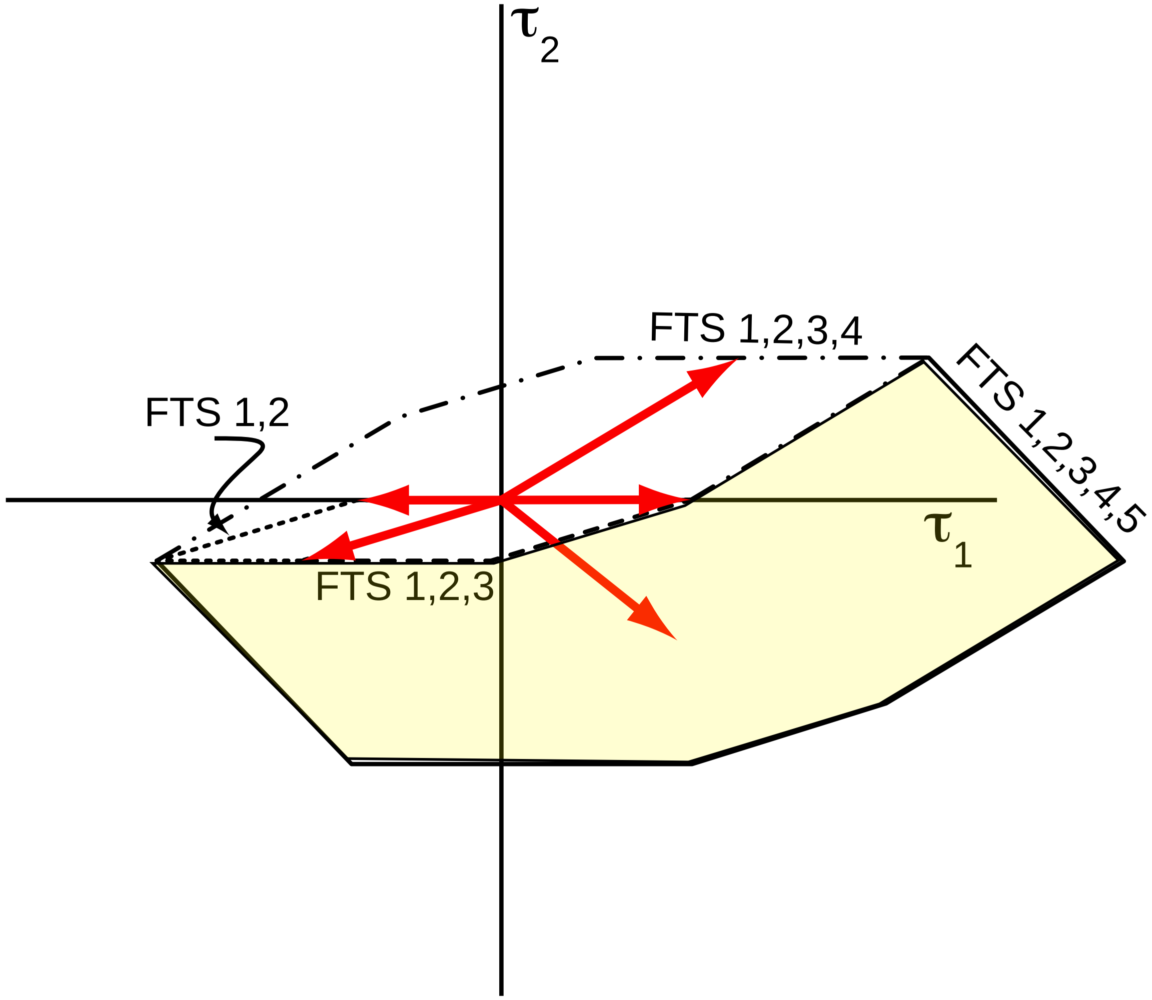
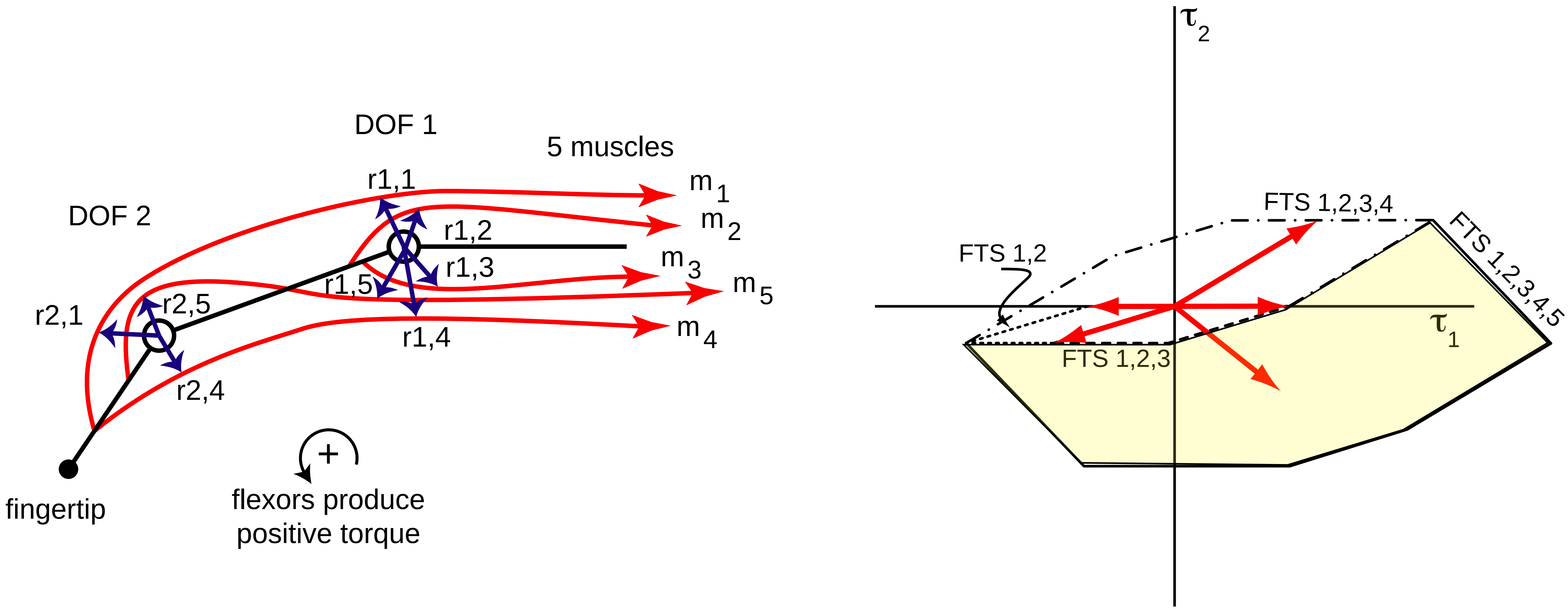




Tendons define the size and shape of the feasible torque and feasible force sets

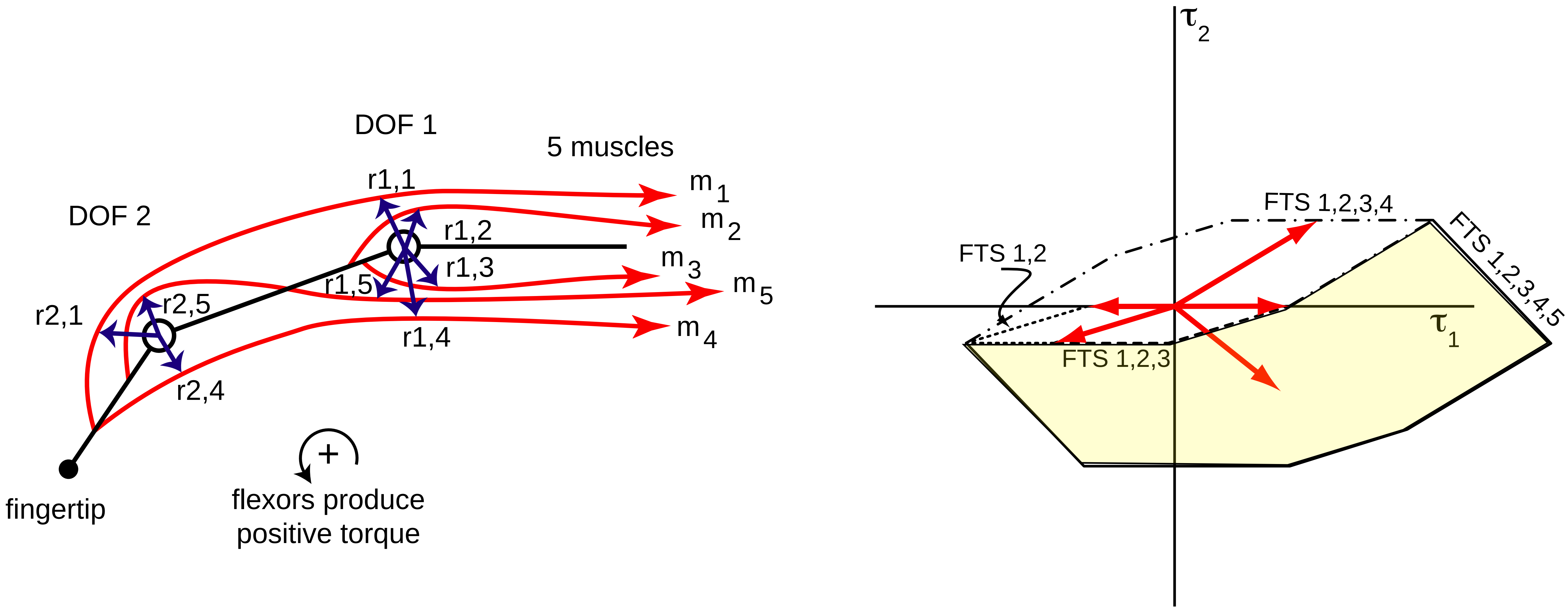
And each tendon contributes in unique ways



Tendons define the size and shape of the feasible torque and feasible force sets

So which muscle would you give up?

And each tendon contributes in unique ways



Tendons define the size and shape of the feasible torque and feasible force sets

So which muscle would you give up?

This begins to explain the evolutionary advantages of encoding, developing, maintaining, repairing, controlling apparently "too many" muscles.

Redundancy does not imply robustness

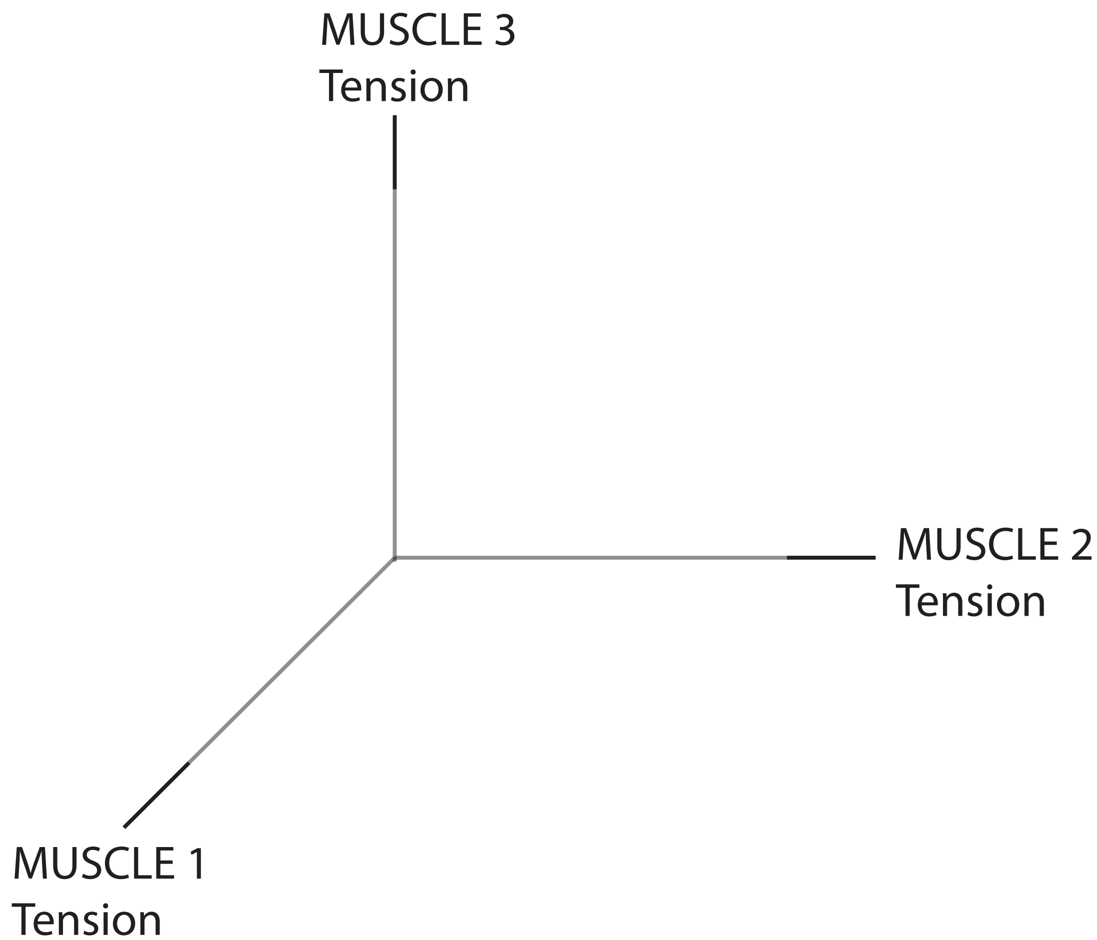
Now assistant professor at USC

With Jason Kutch

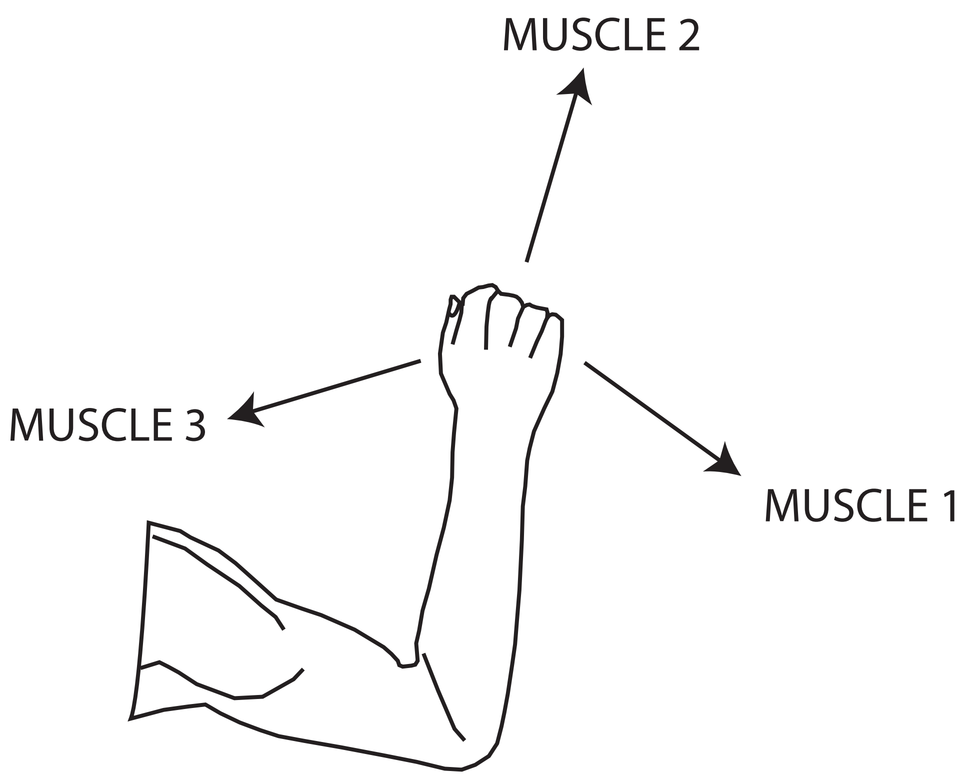
J Biomech 2011

Dimensionality and structure of the solution space

feasible input space



feasible output space



Computational Geometry

Vertex Enumeration (dual of Linear programming)

No cost function needed, simply description of feasible inputs and outputs!

Valero-Cuevas et al., 1998, 2005, 2009; Kutch & Valero-Cuevas, Inouye and Valero-Cuevas 2011

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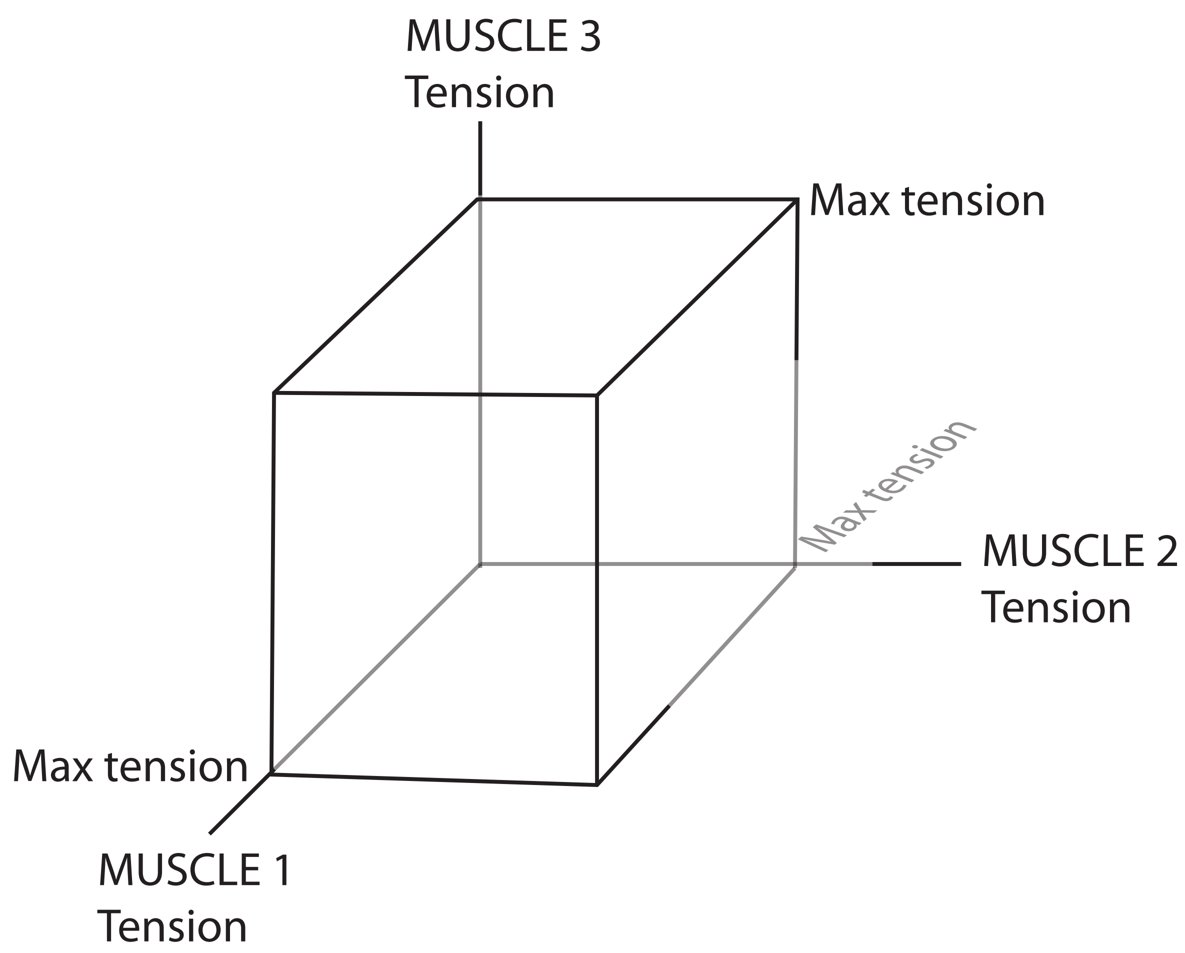

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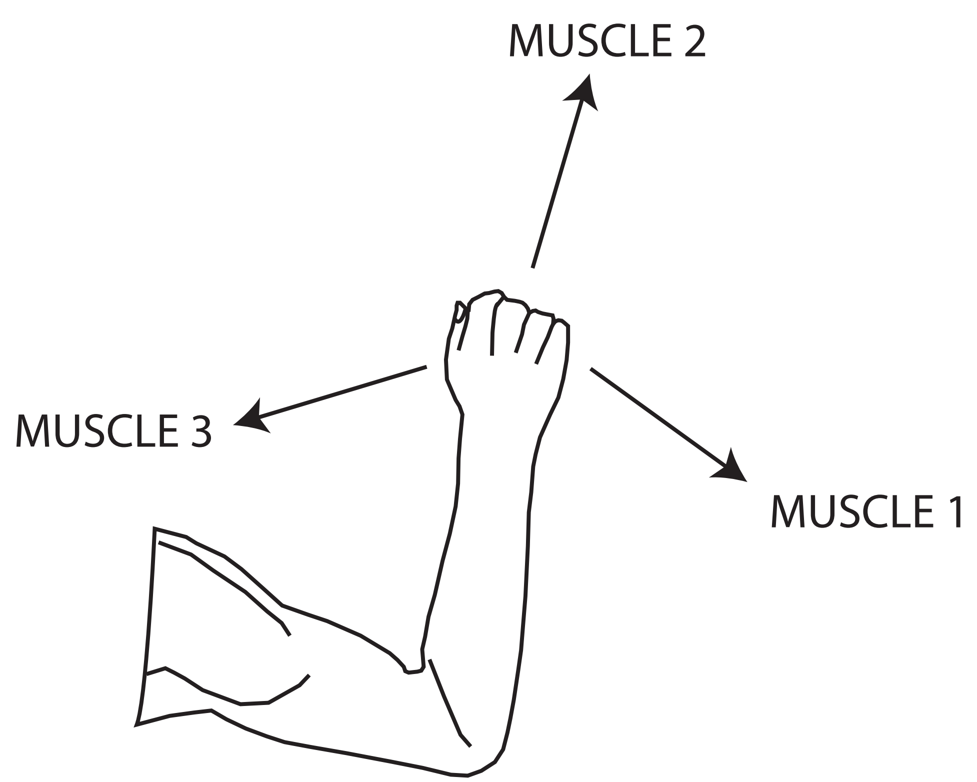

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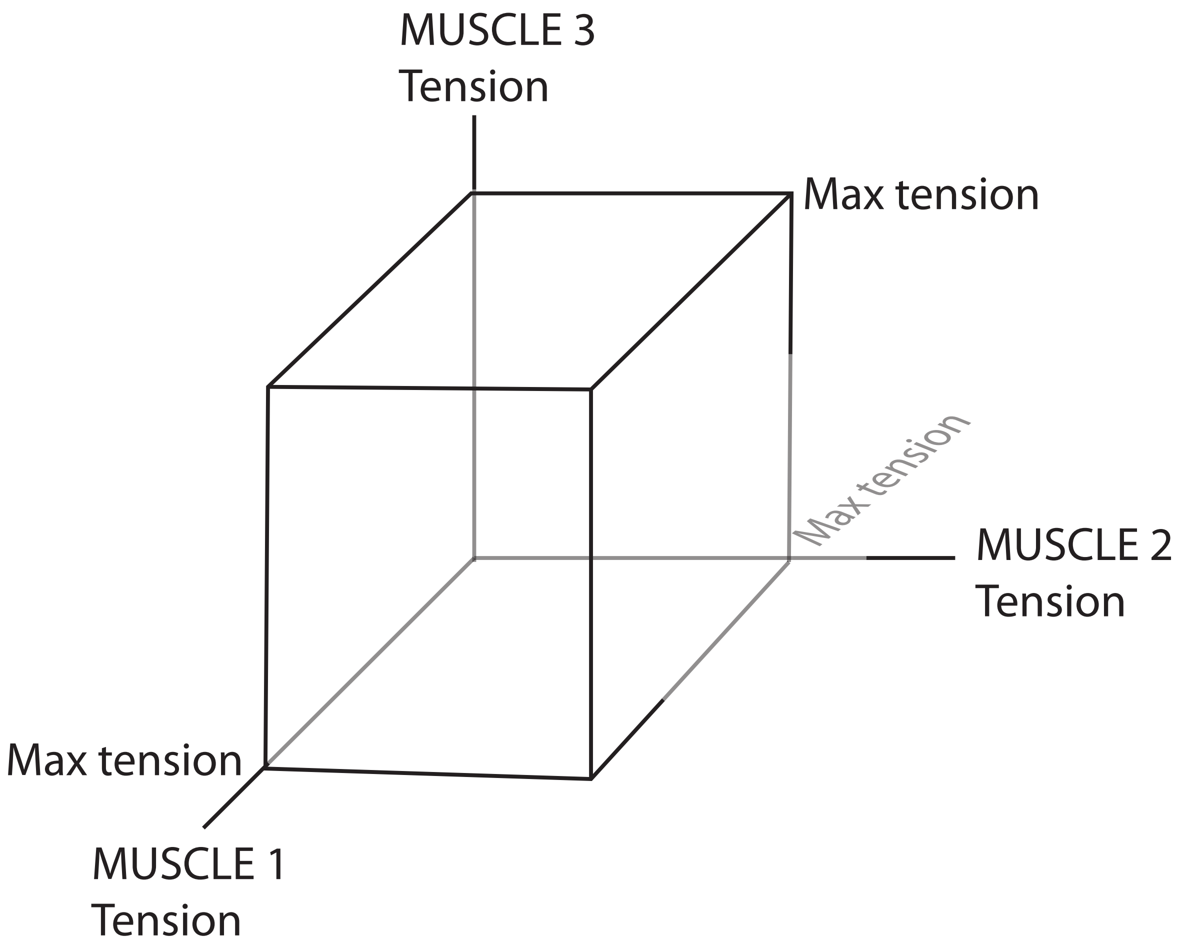

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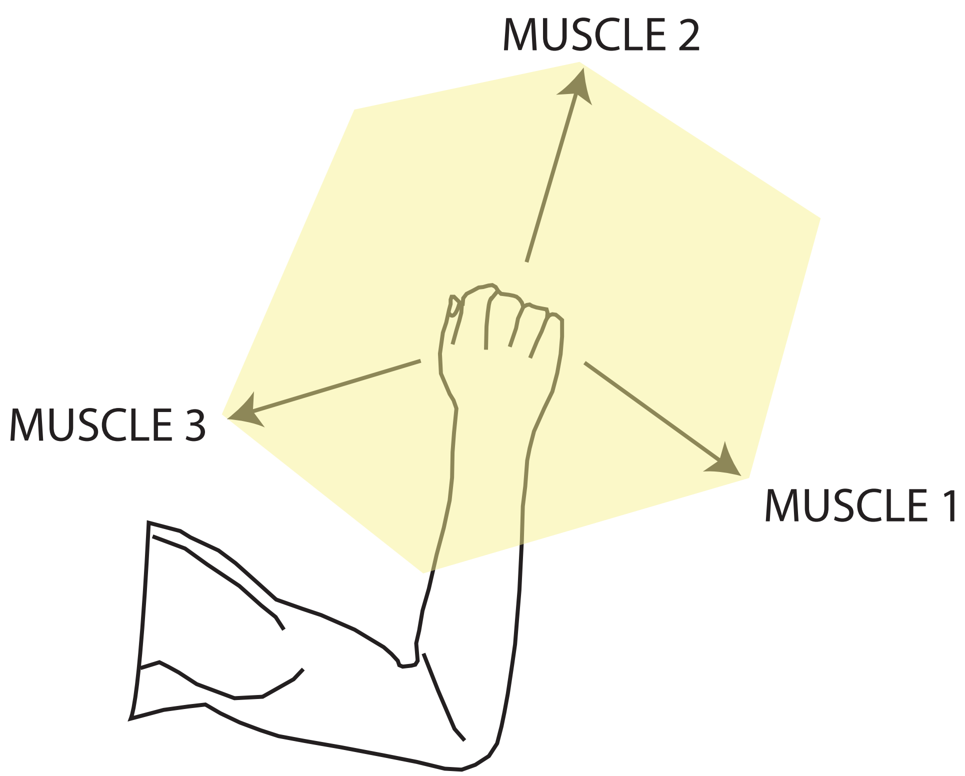

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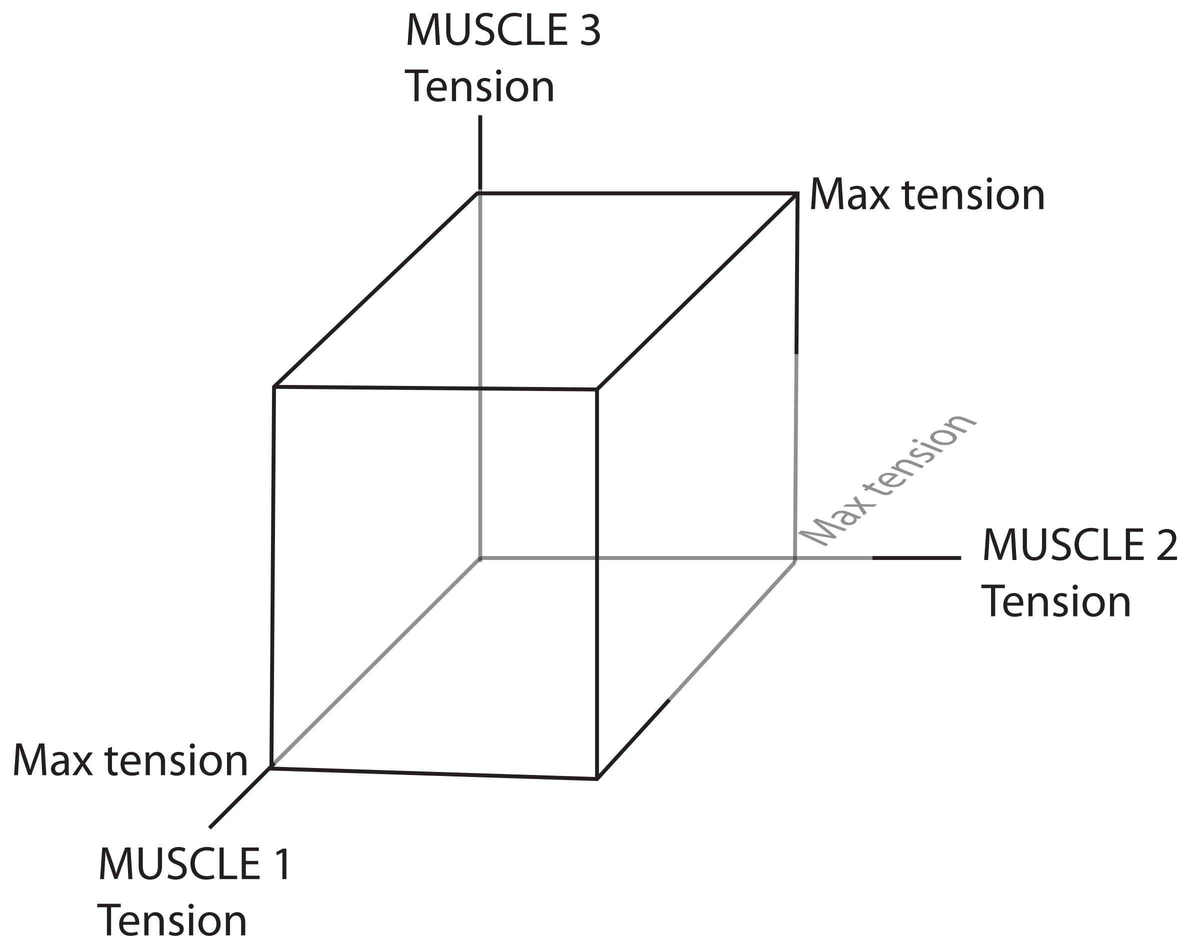

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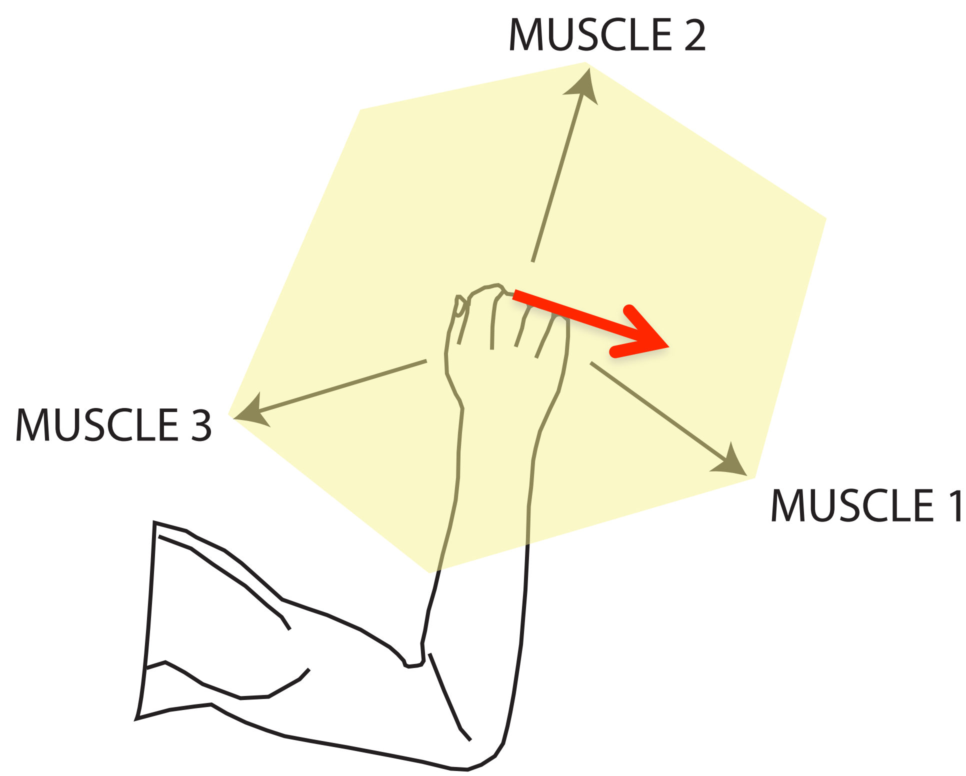

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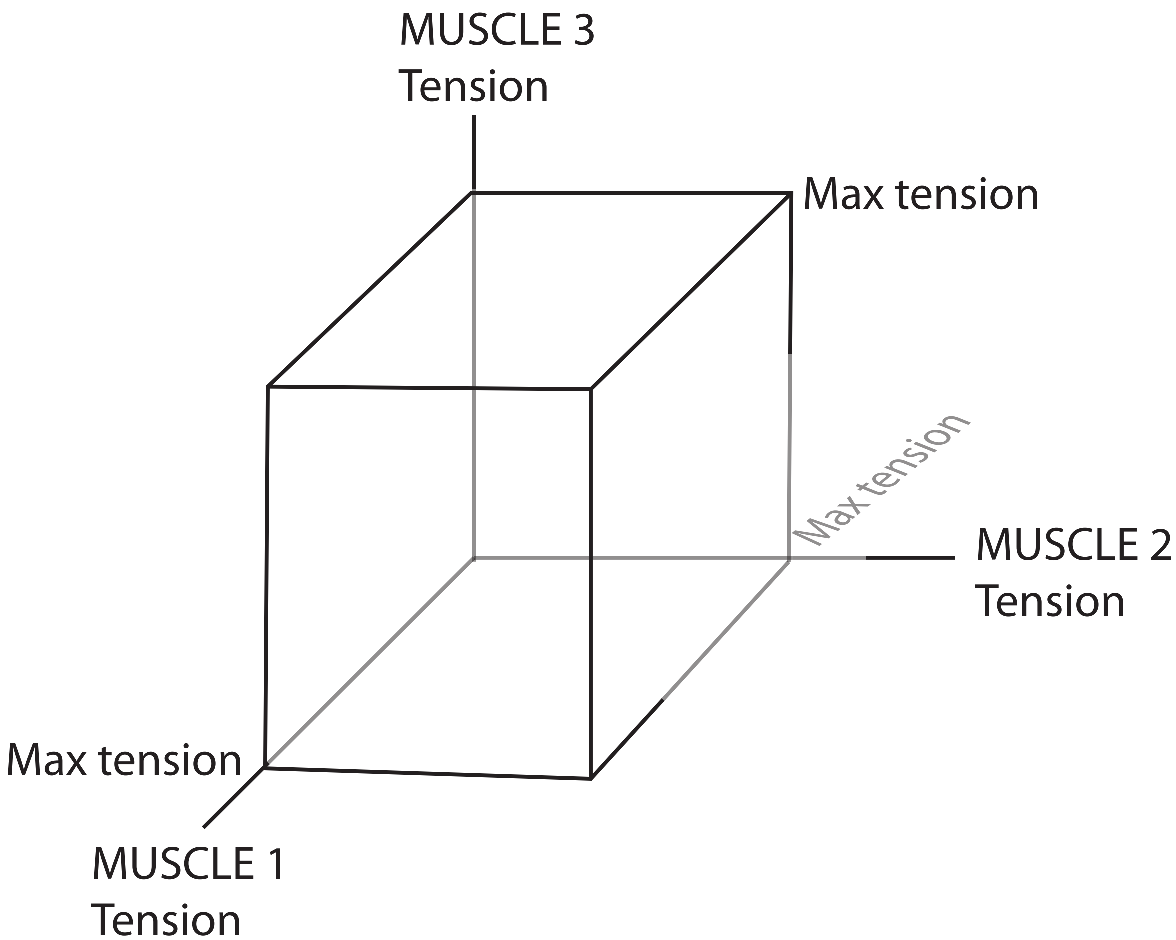

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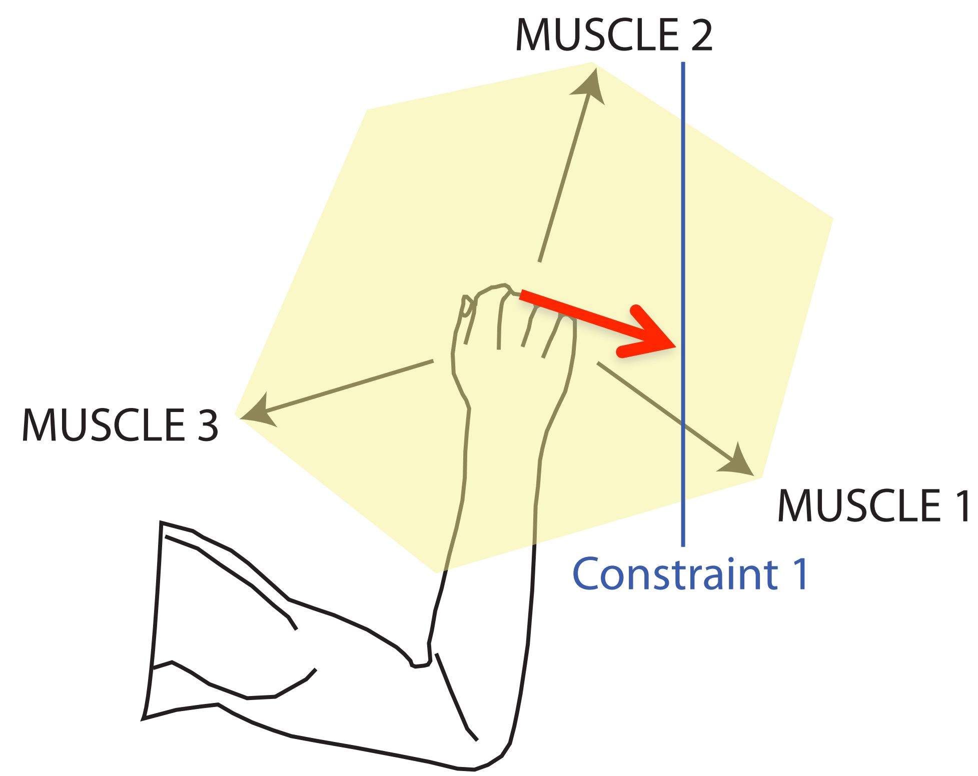

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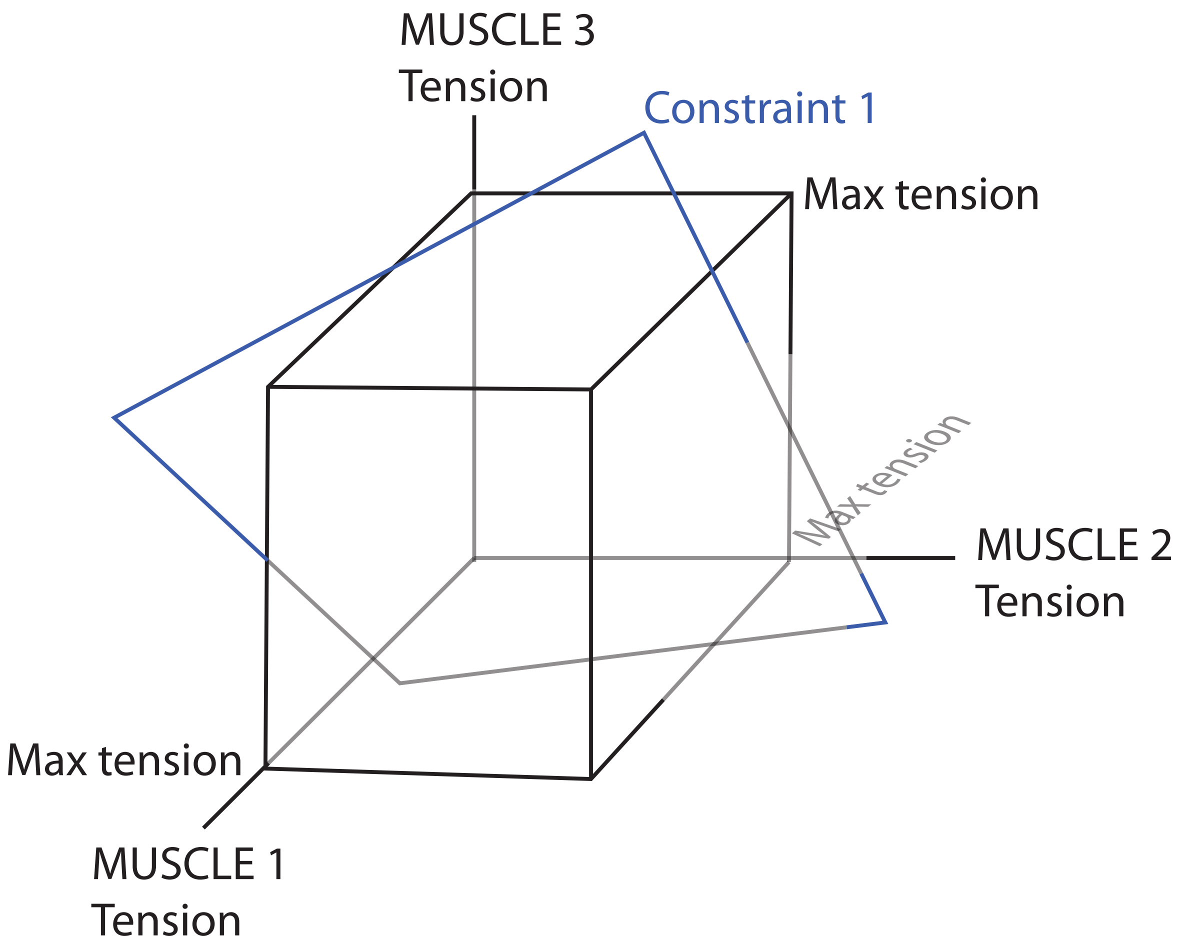

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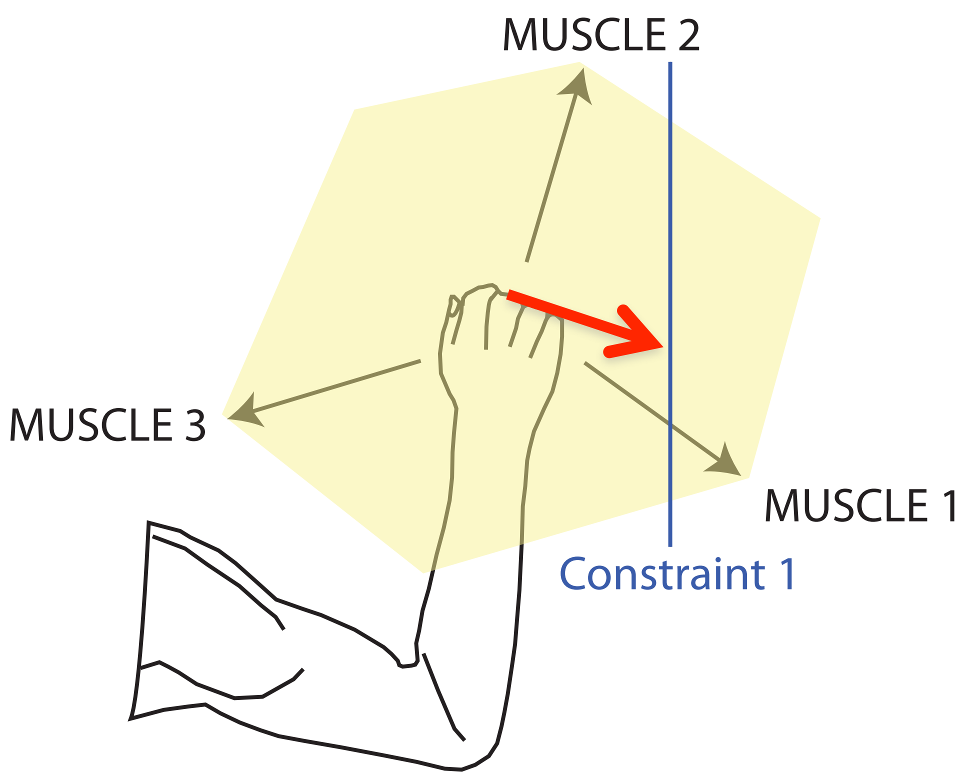

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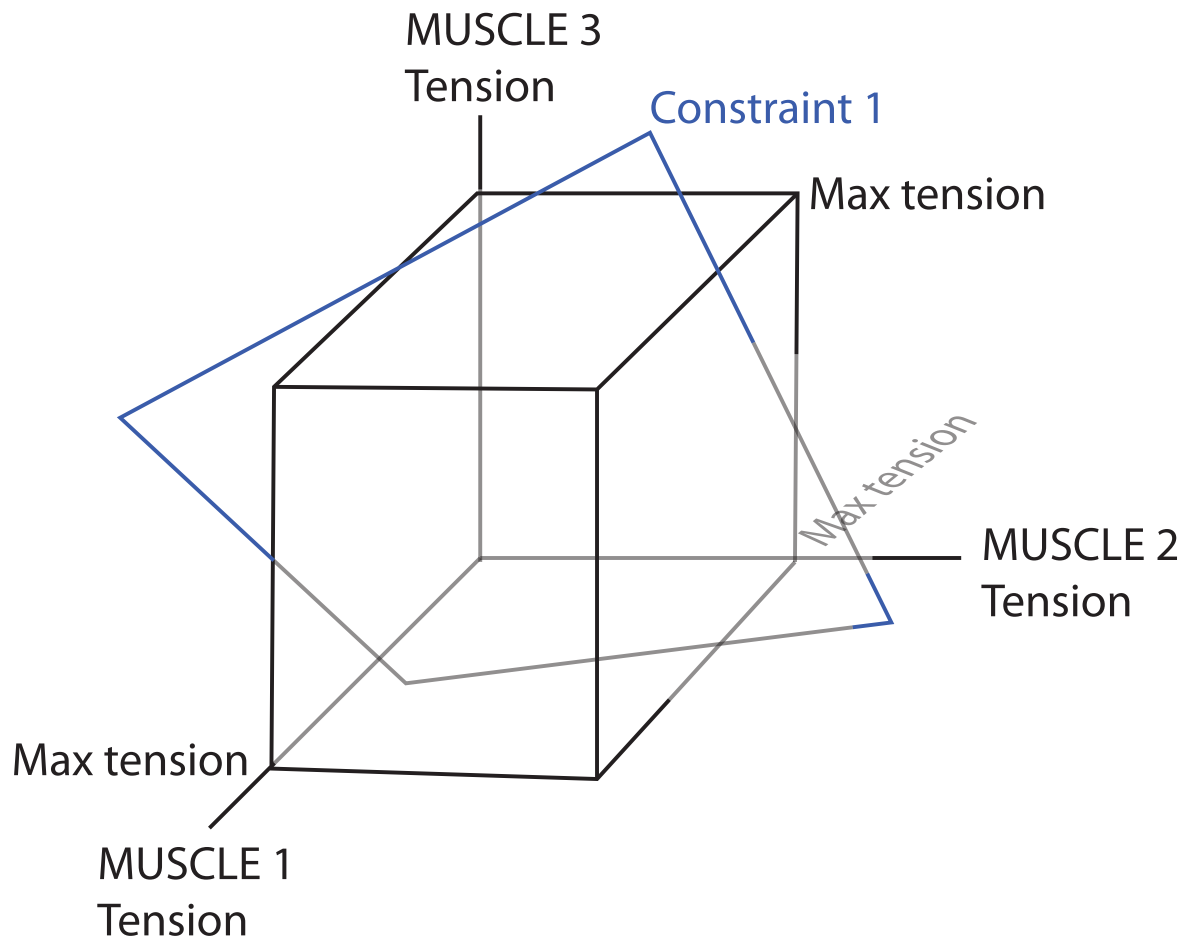

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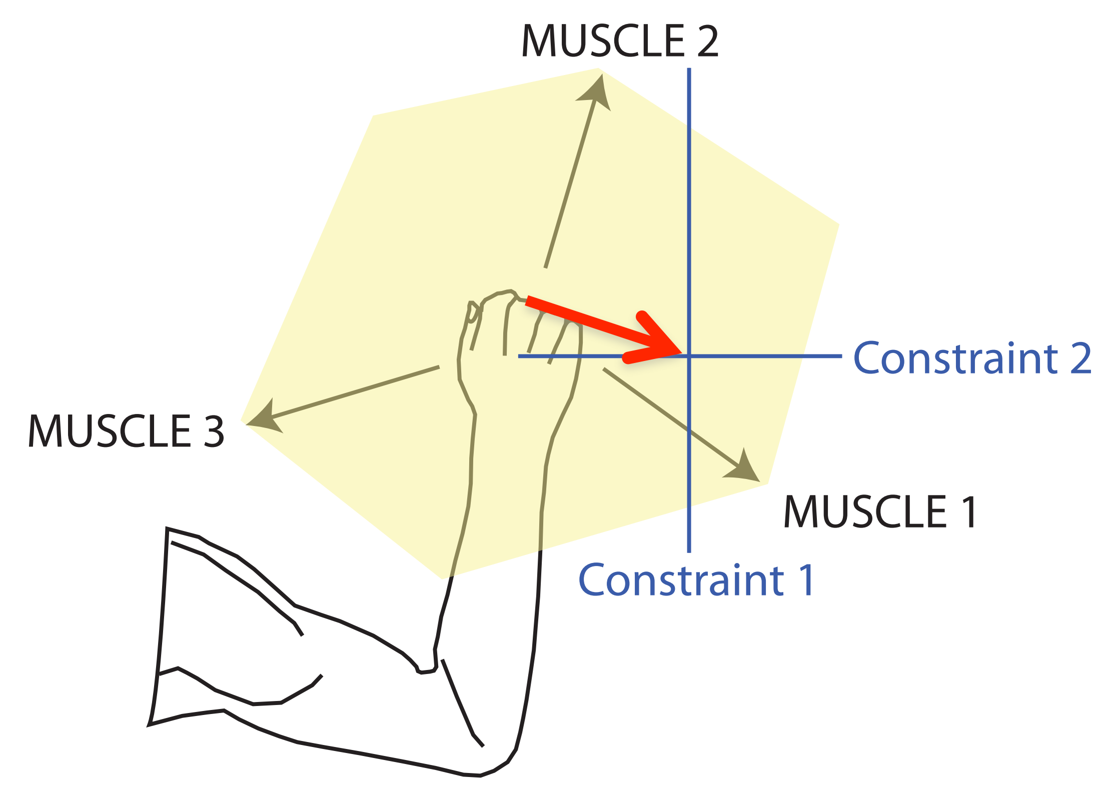

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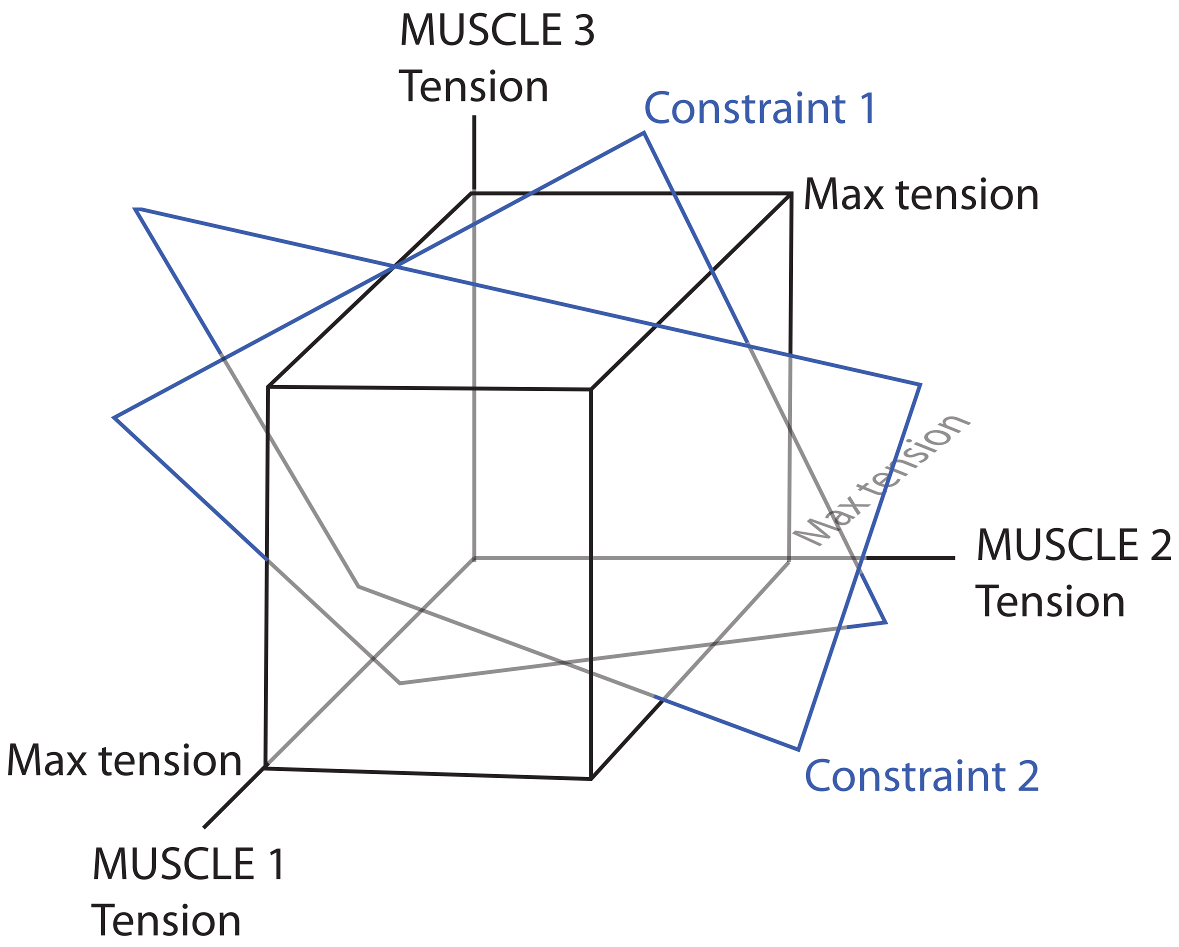

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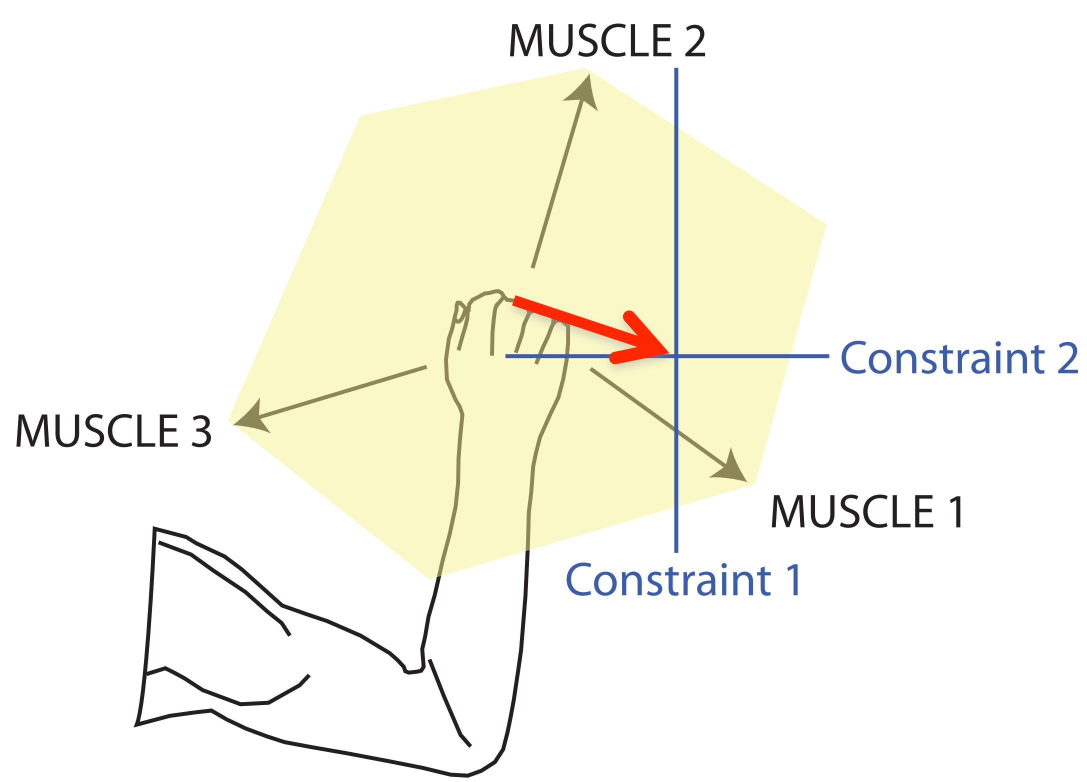

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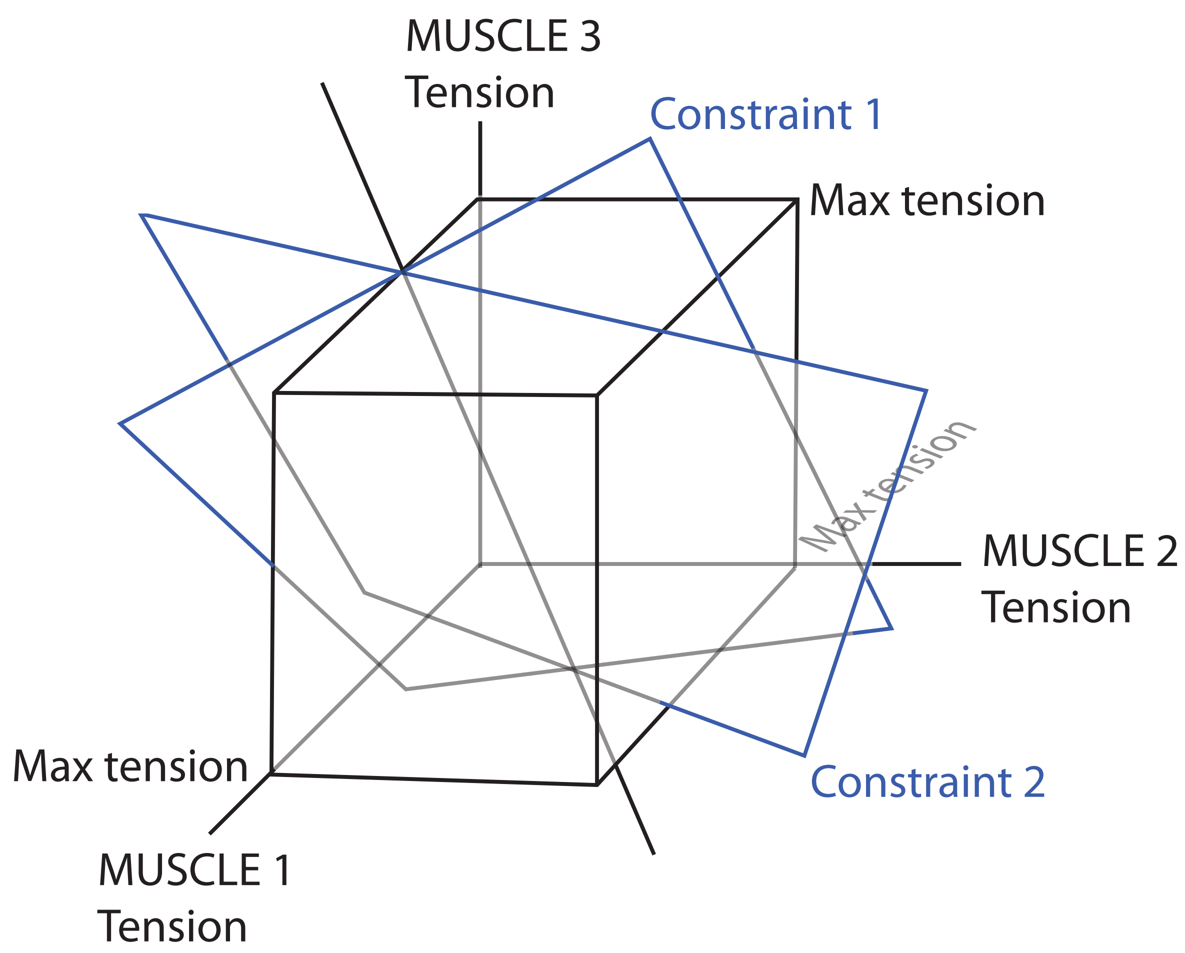

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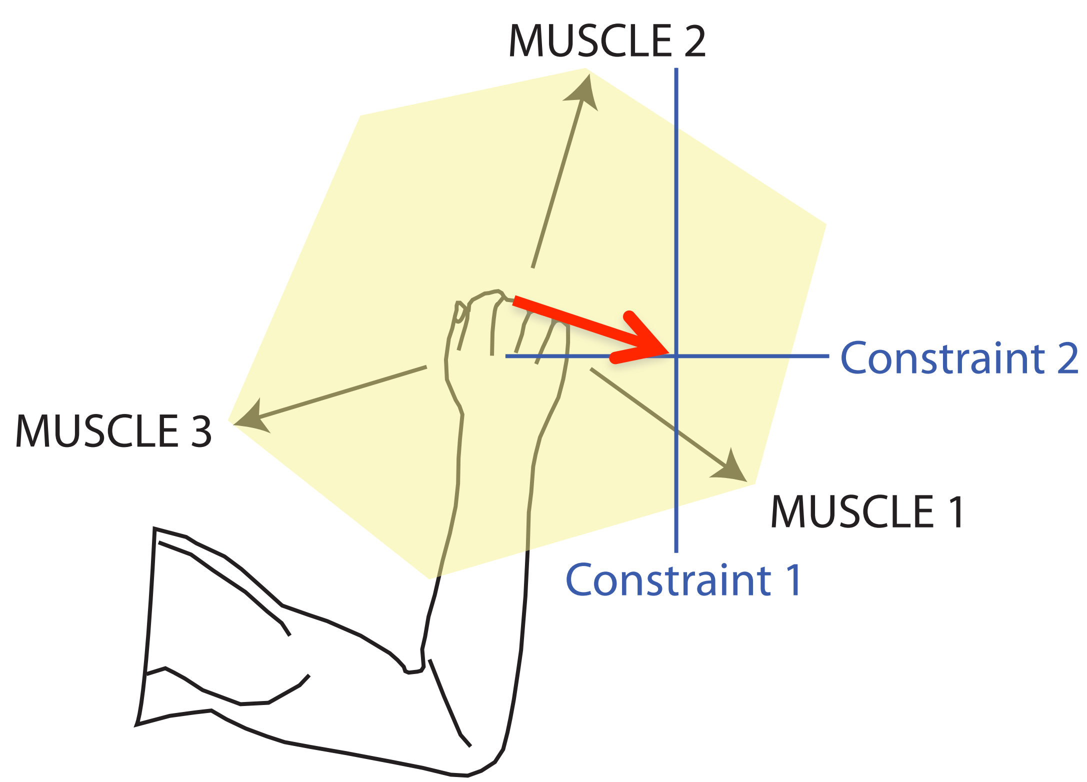

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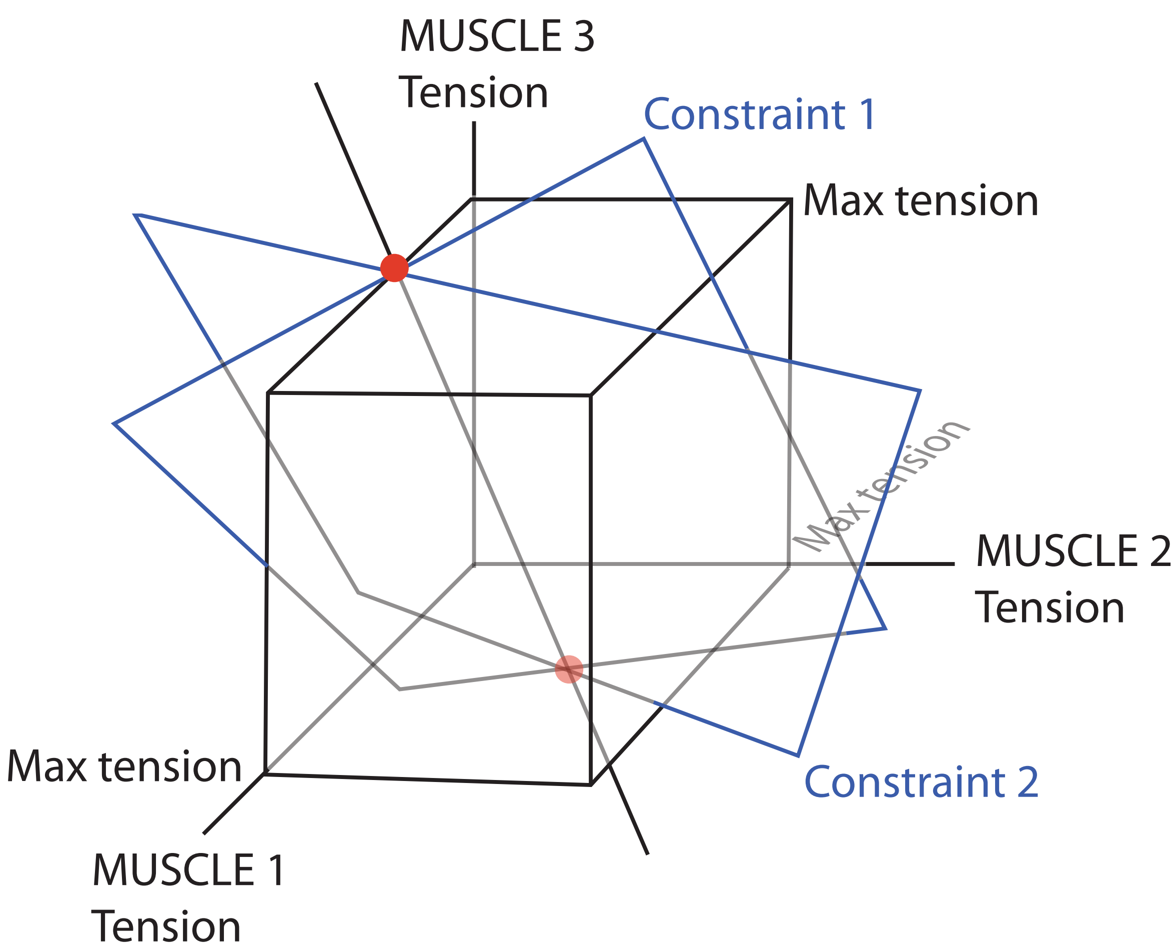

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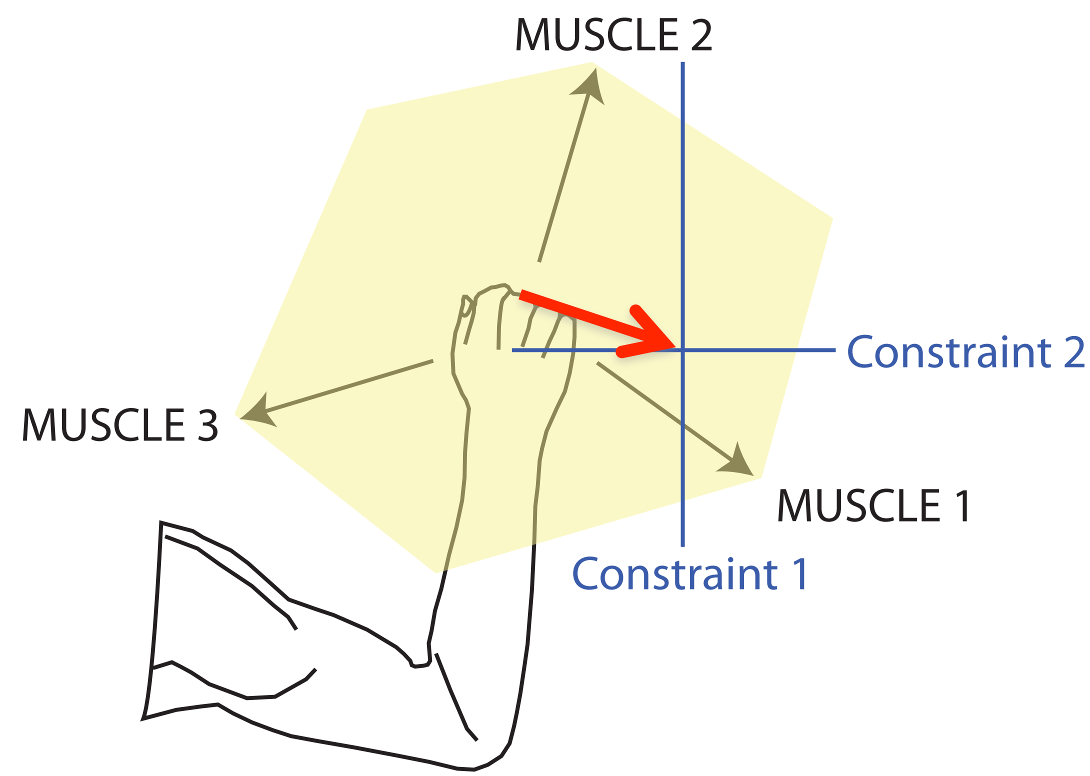

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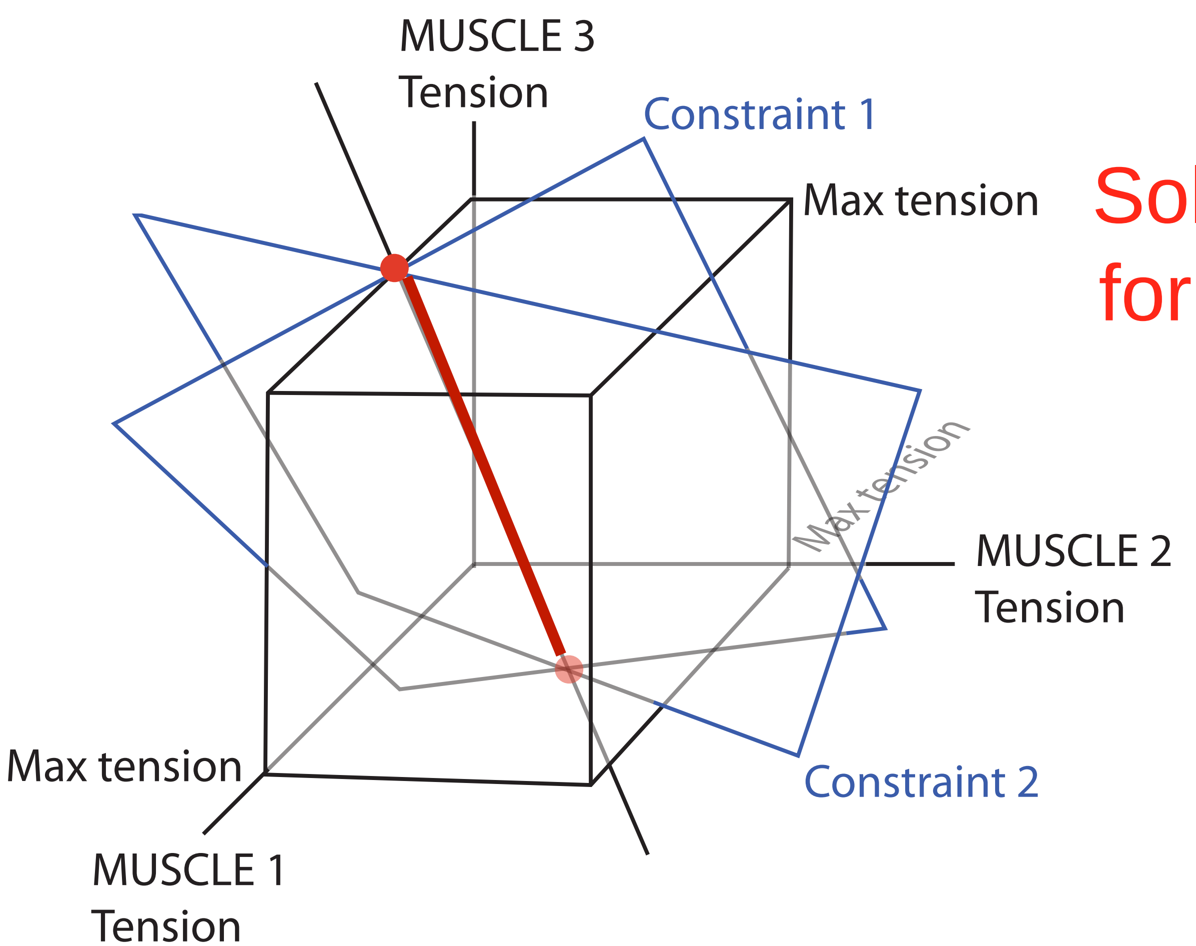
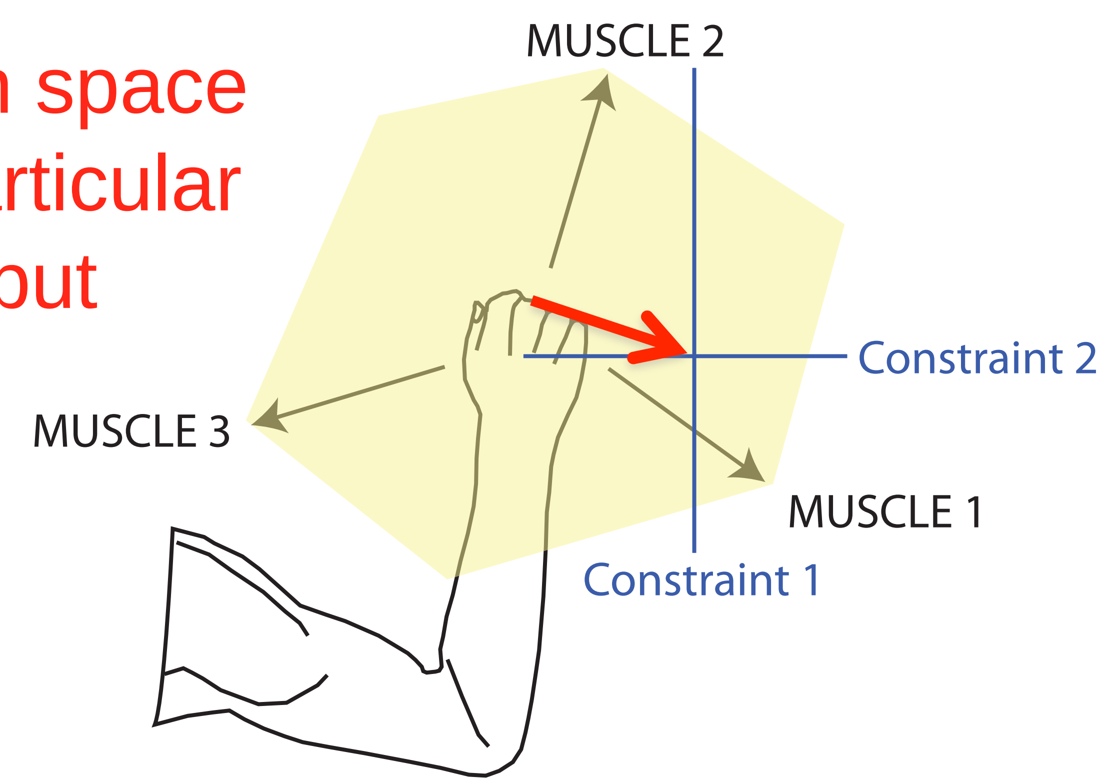


Solution space for a particular output



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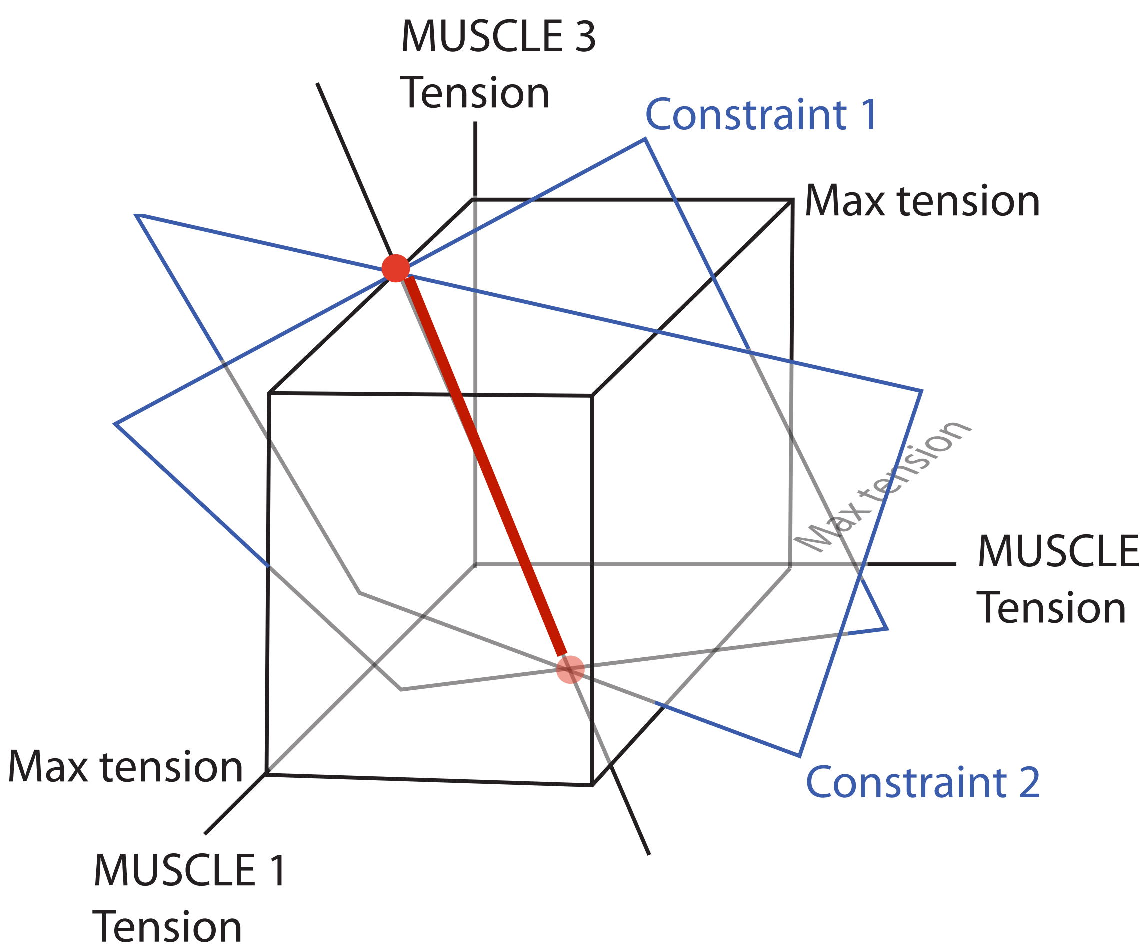
Relationship between task constraints, number of muscles and redundancy

feasible input space



Valero-Cuevas 1998

Motor Control, 2000, **4**, 81-83

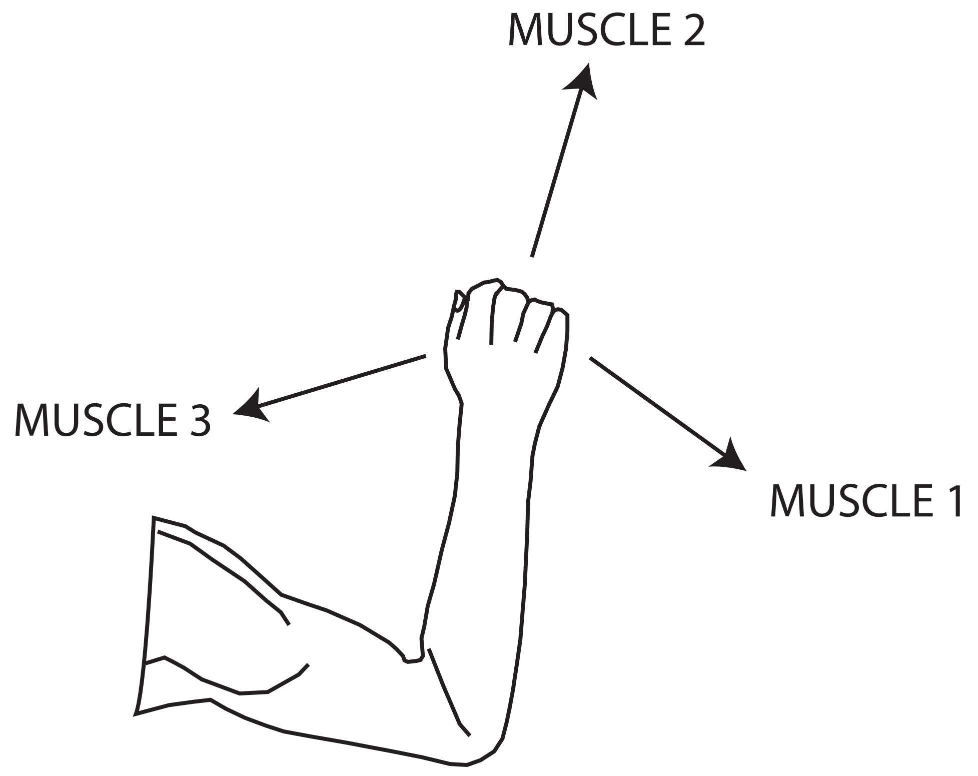
Overcomplete Musculature or Underspecified Tasks?

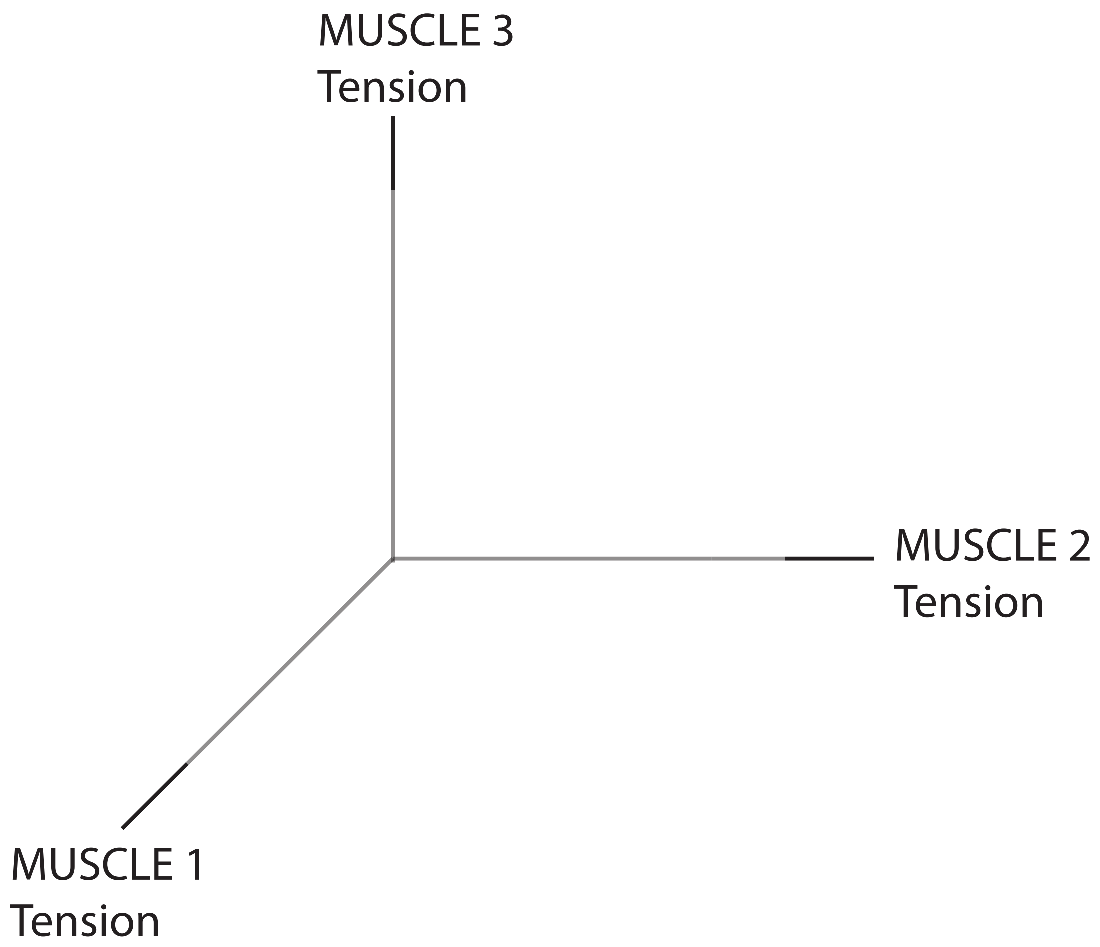
Gerald E. Loeb

The number of muscles in the body is actually fairly close to the number required to control completely all its degrees of freedom. The apparent need for a coordinating principle arises from the experimental practice of asking subjects to perform simple movements and assuming that they make no implicit assumptions about other constraints. Natural activities include implicit constraints that differ greatly for different tasks and circumstances and that would be met best by a nervous system free of a priori principles.

***Key Words*:** control, redundancy, degrees of freedom, muscles

Solution space for a particular output





Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011

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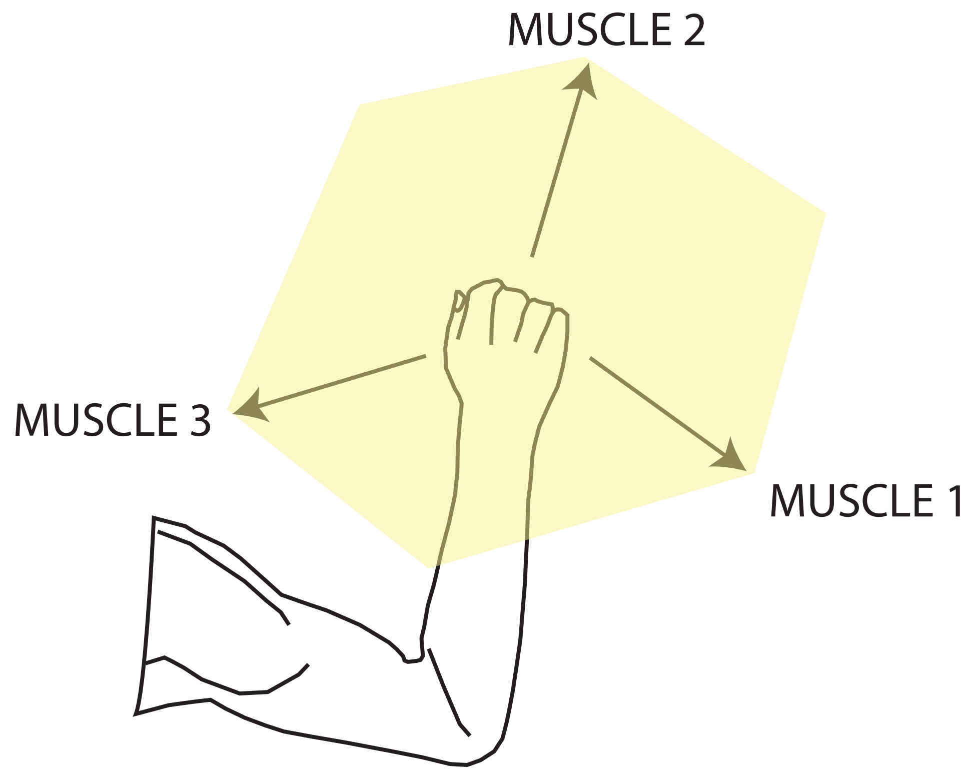

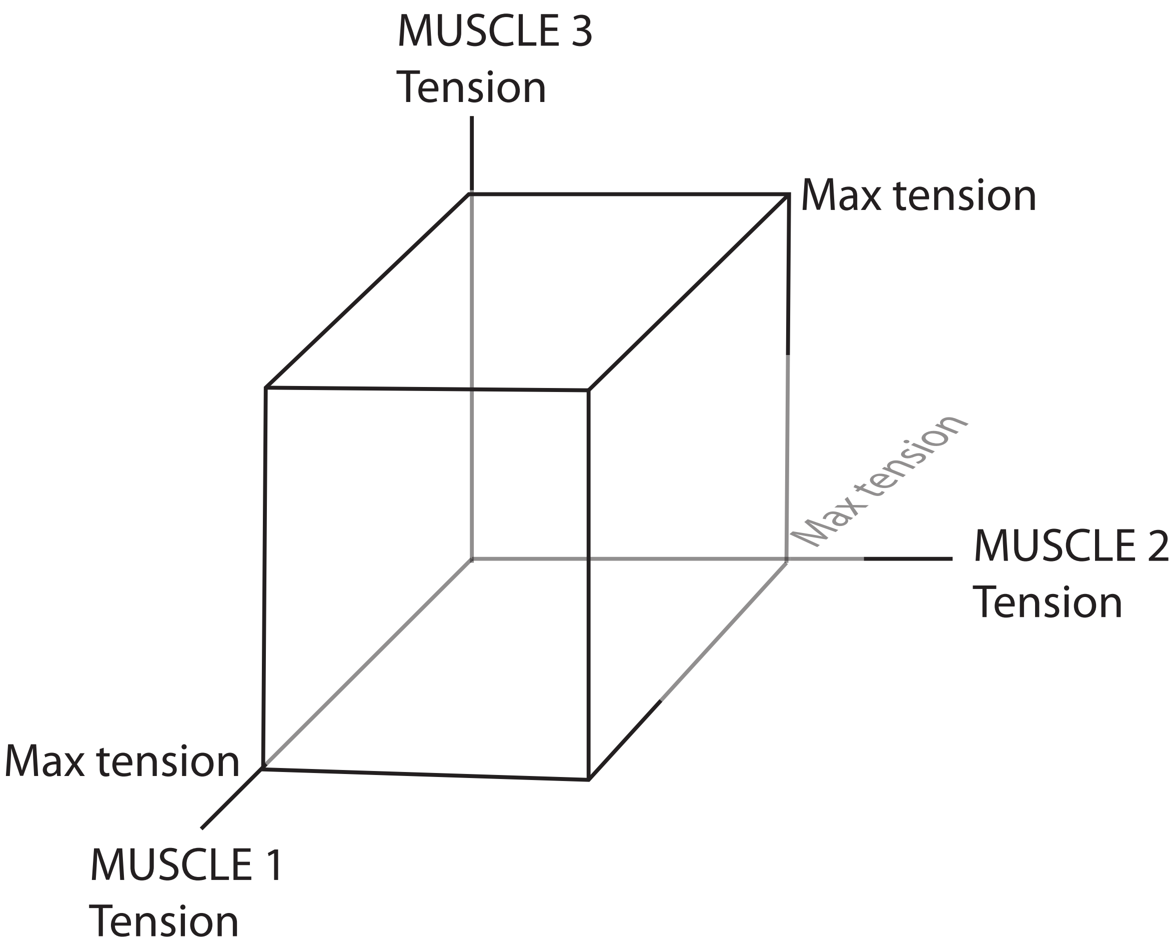

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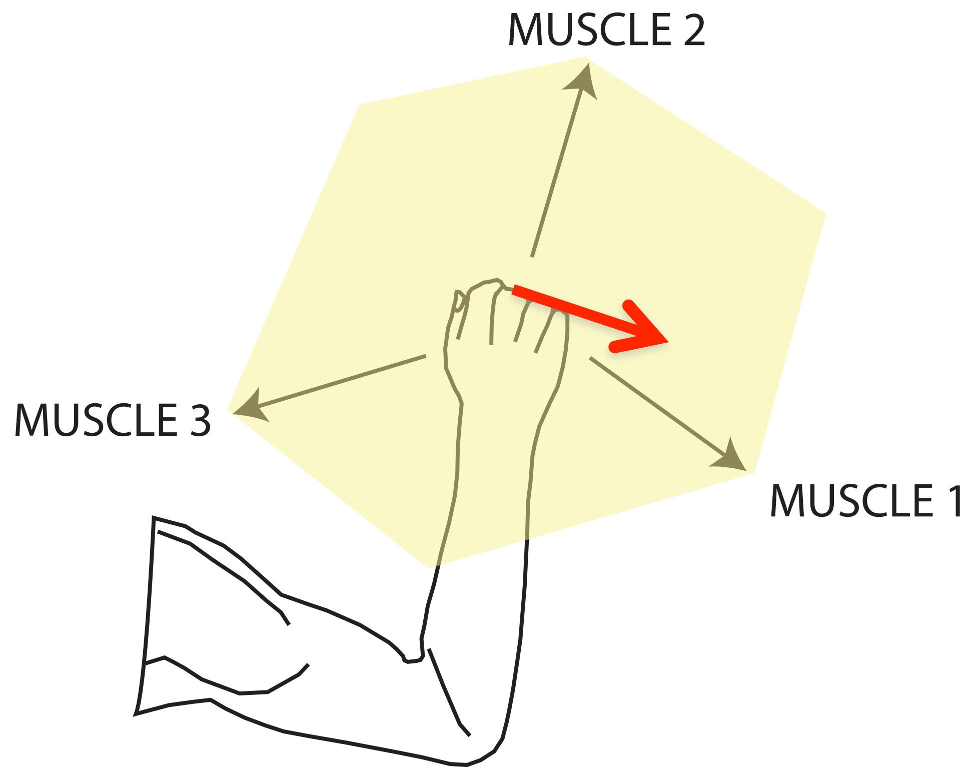

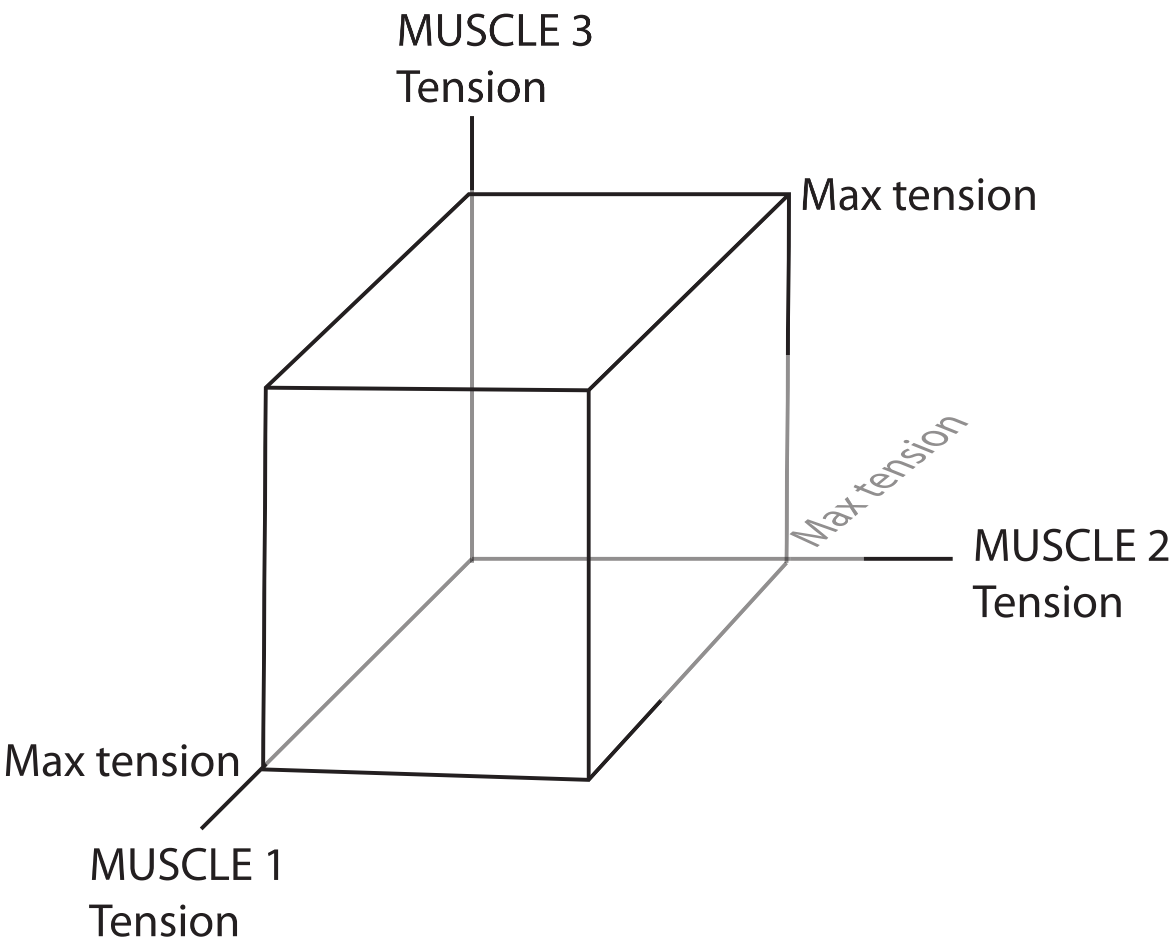

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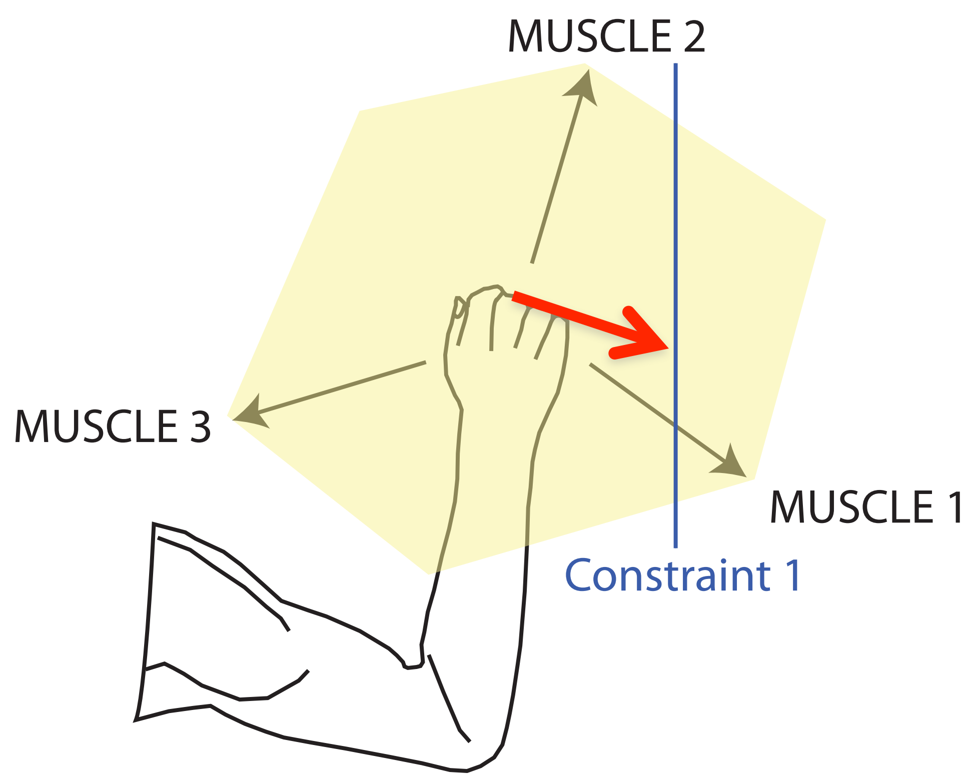

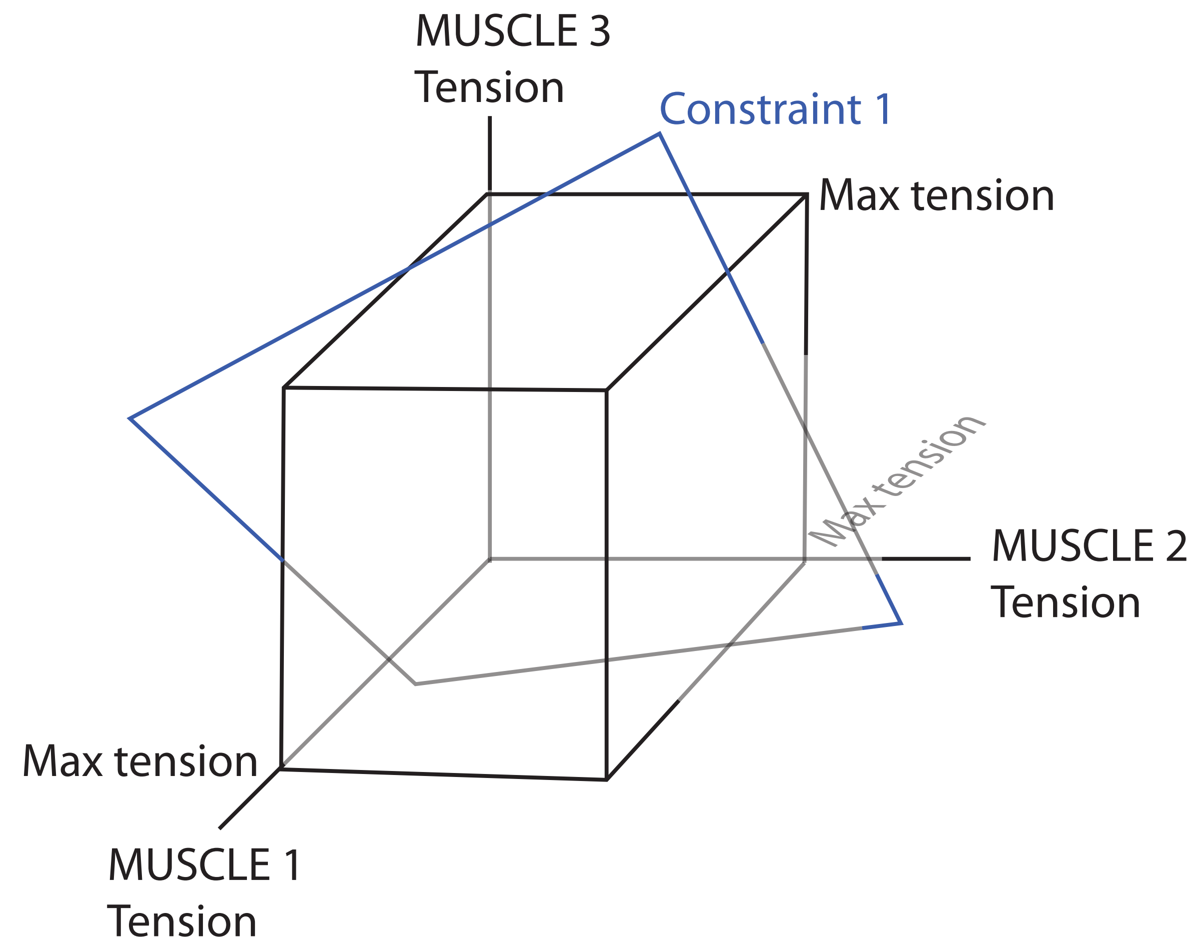

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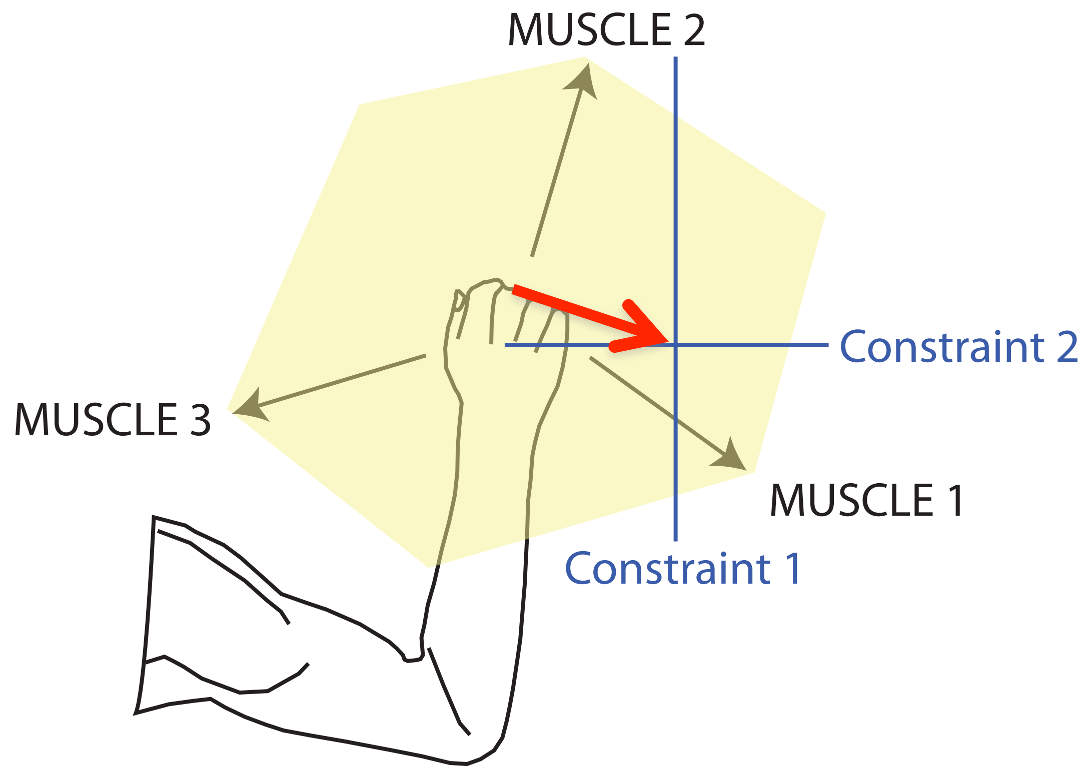

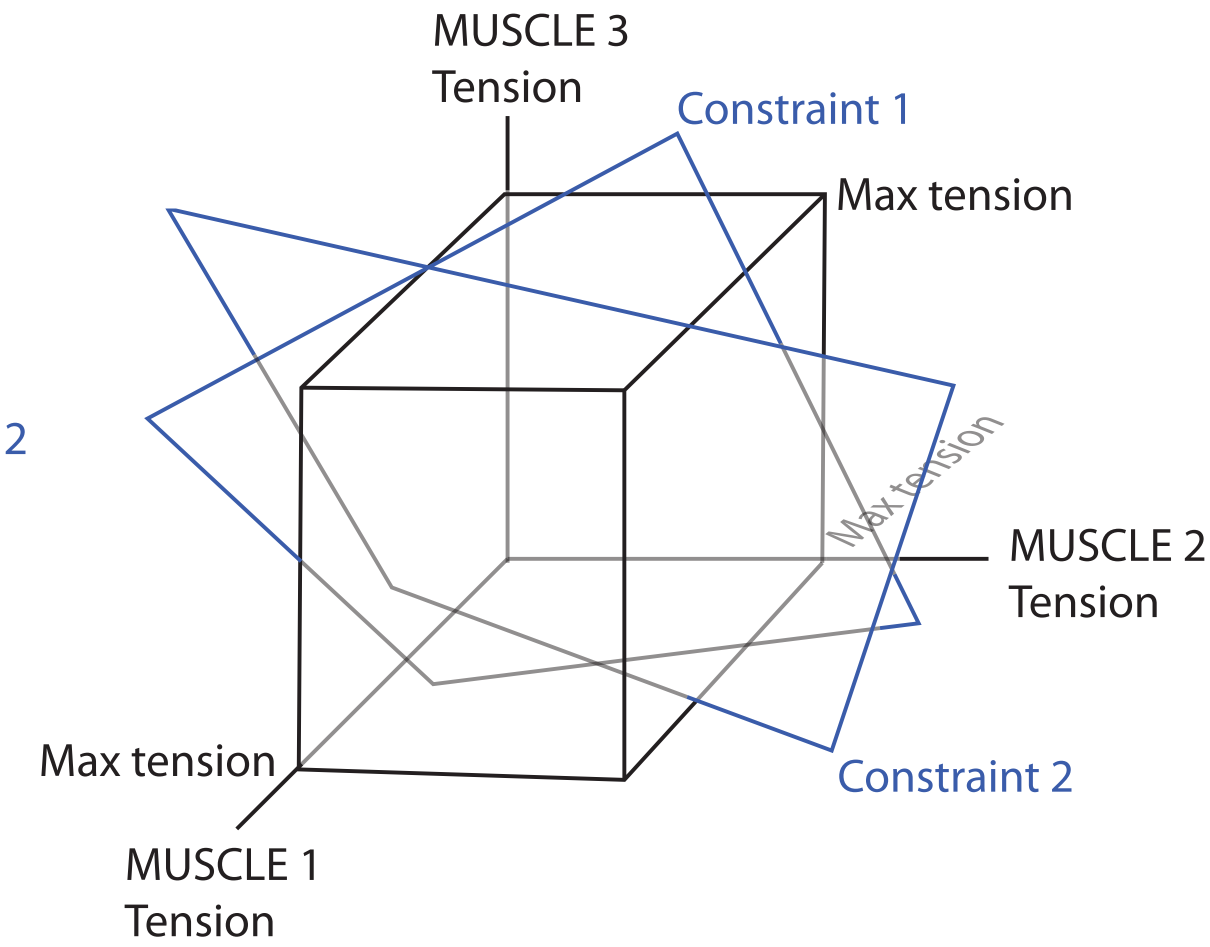

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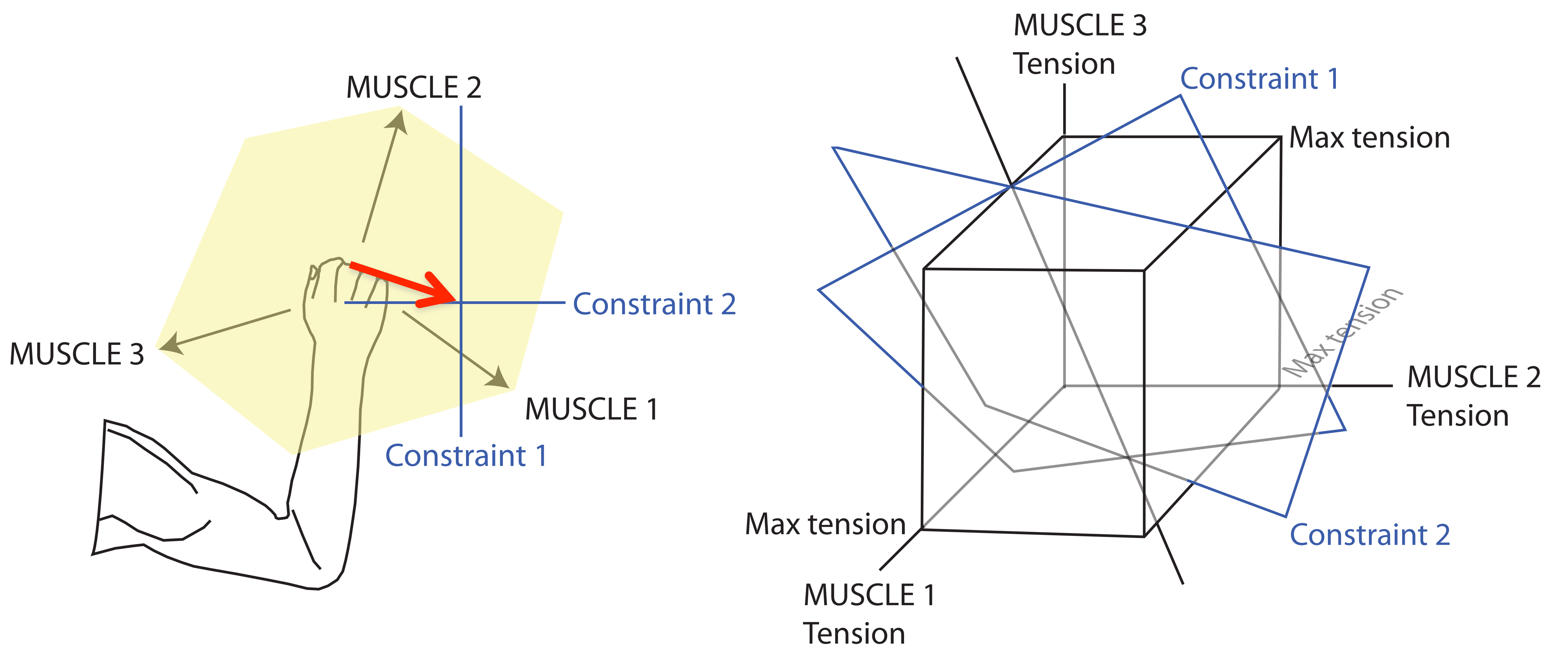

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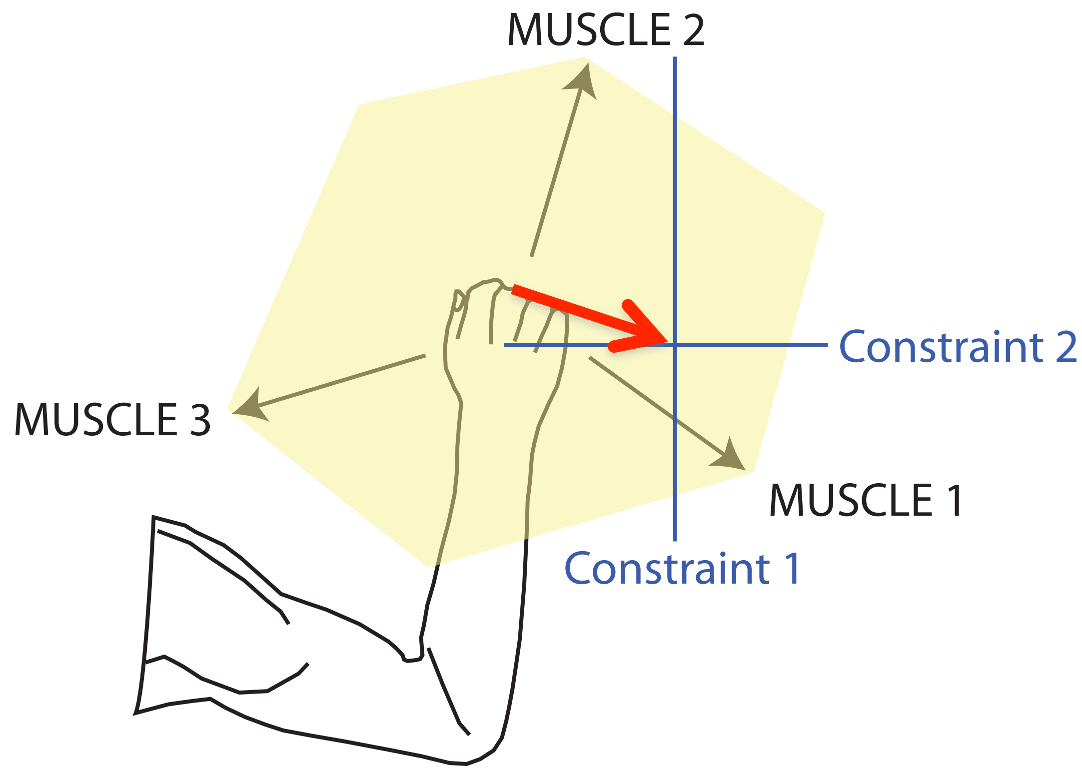

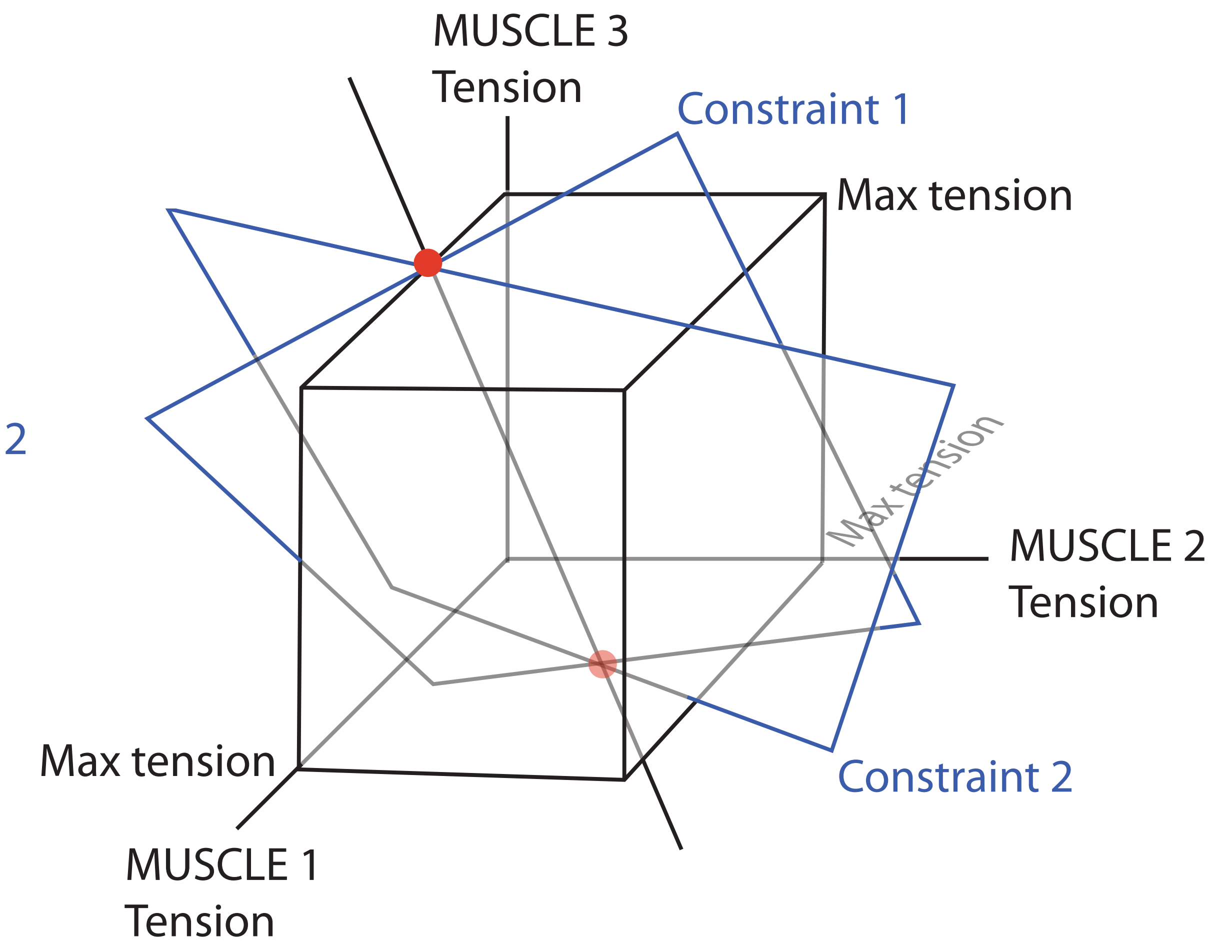

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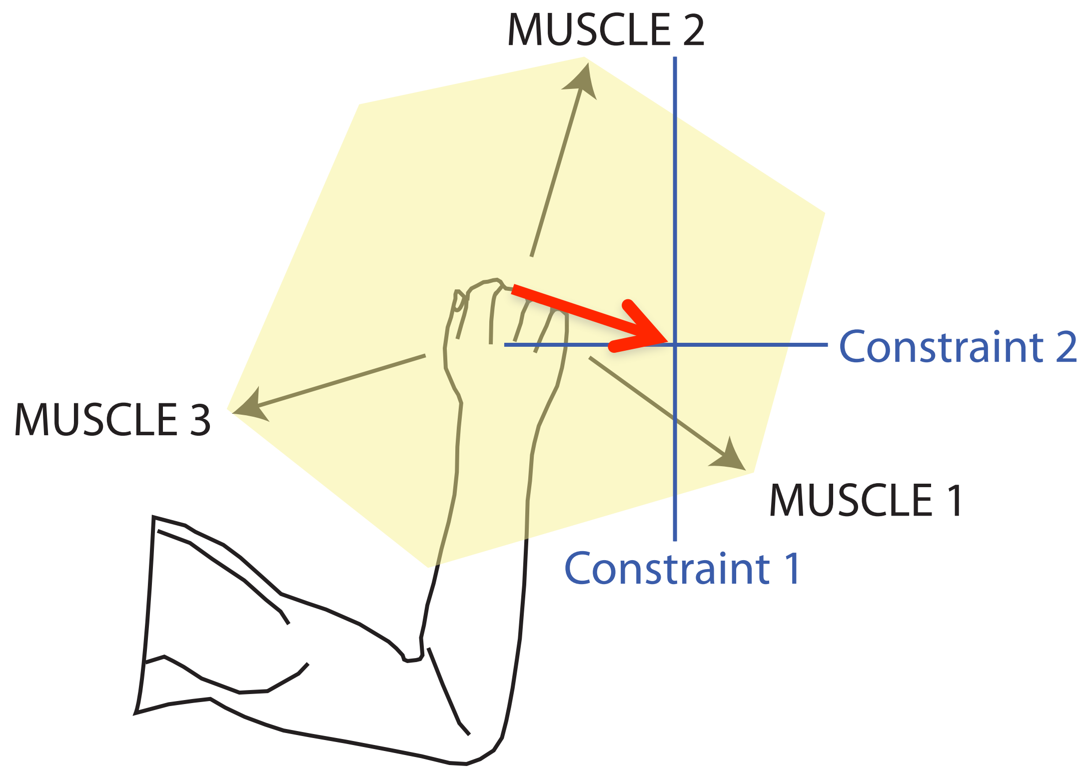

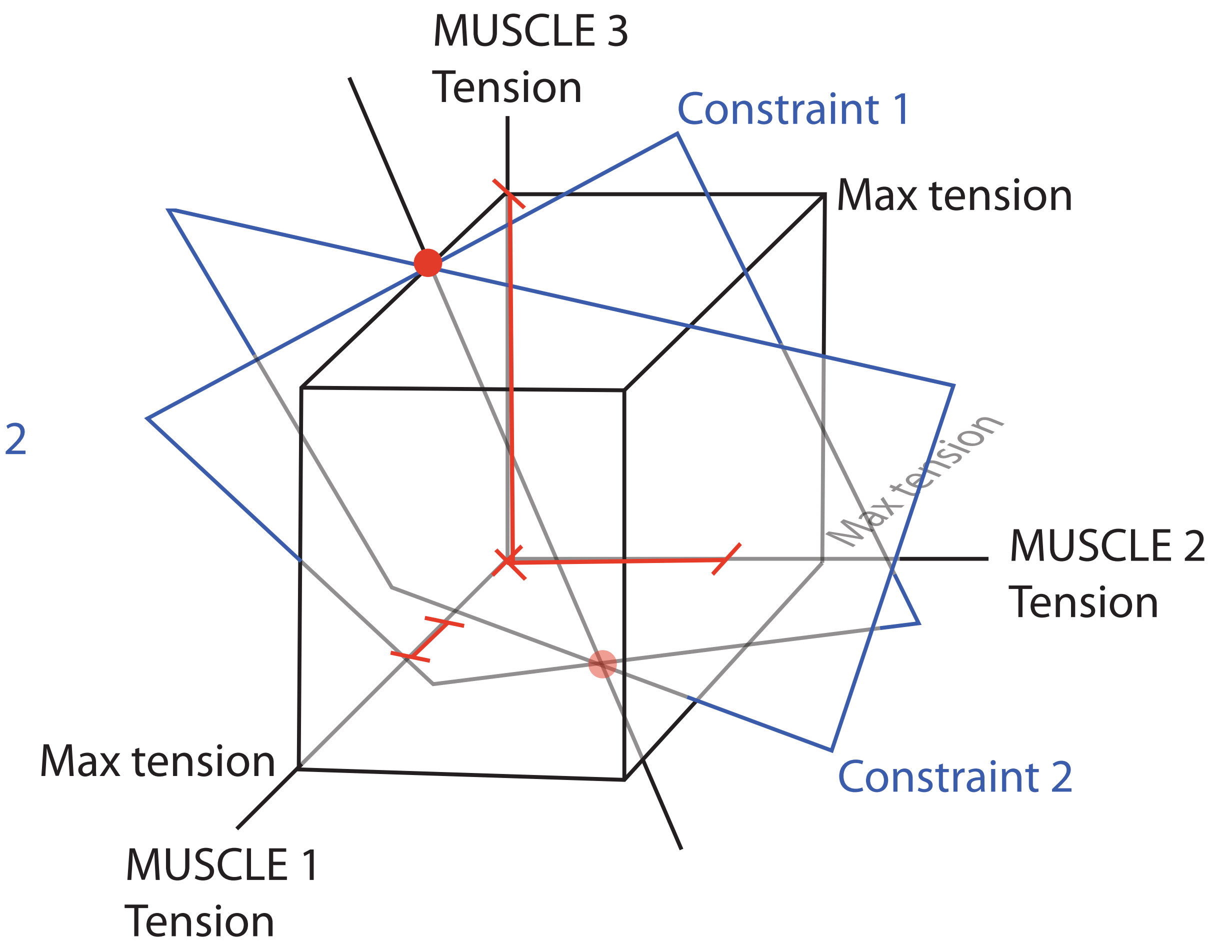

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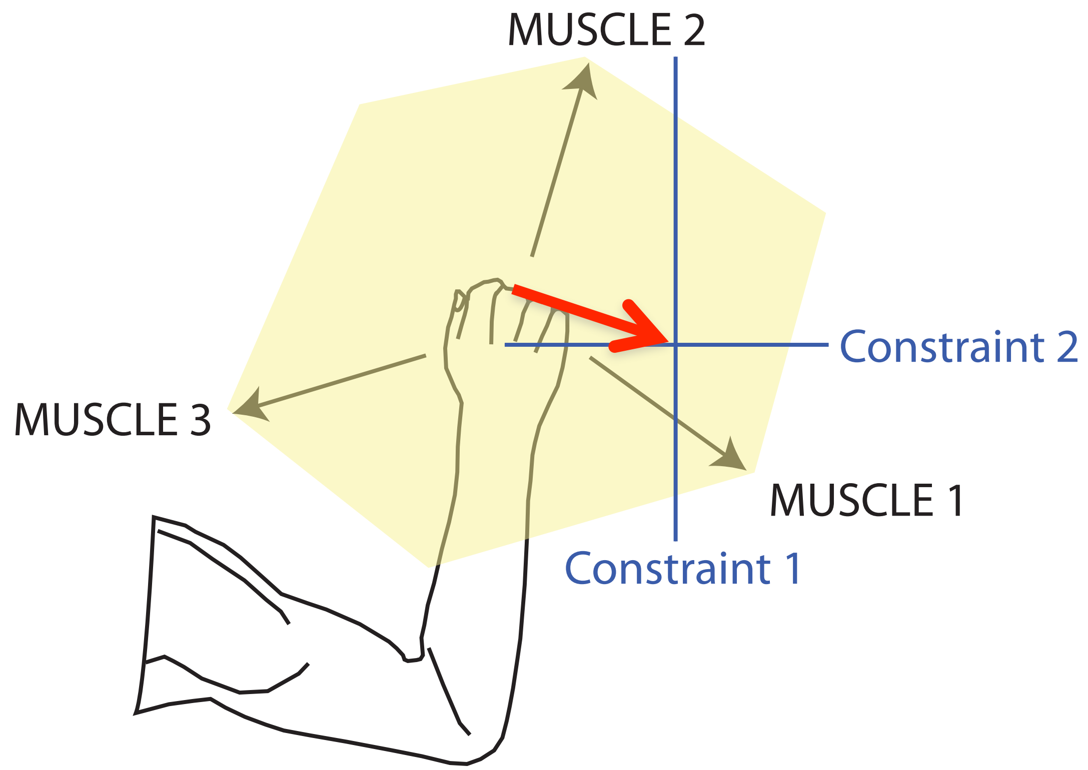

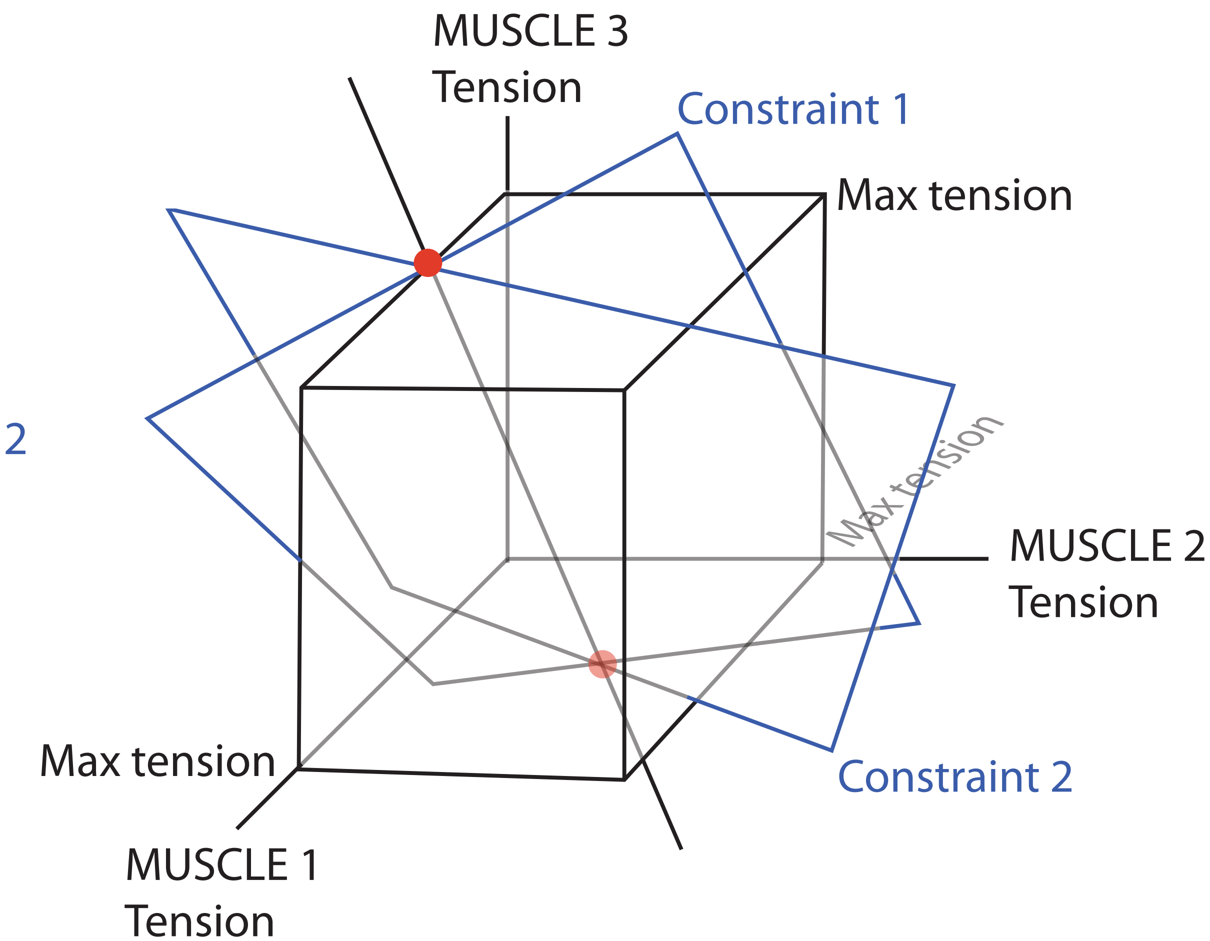

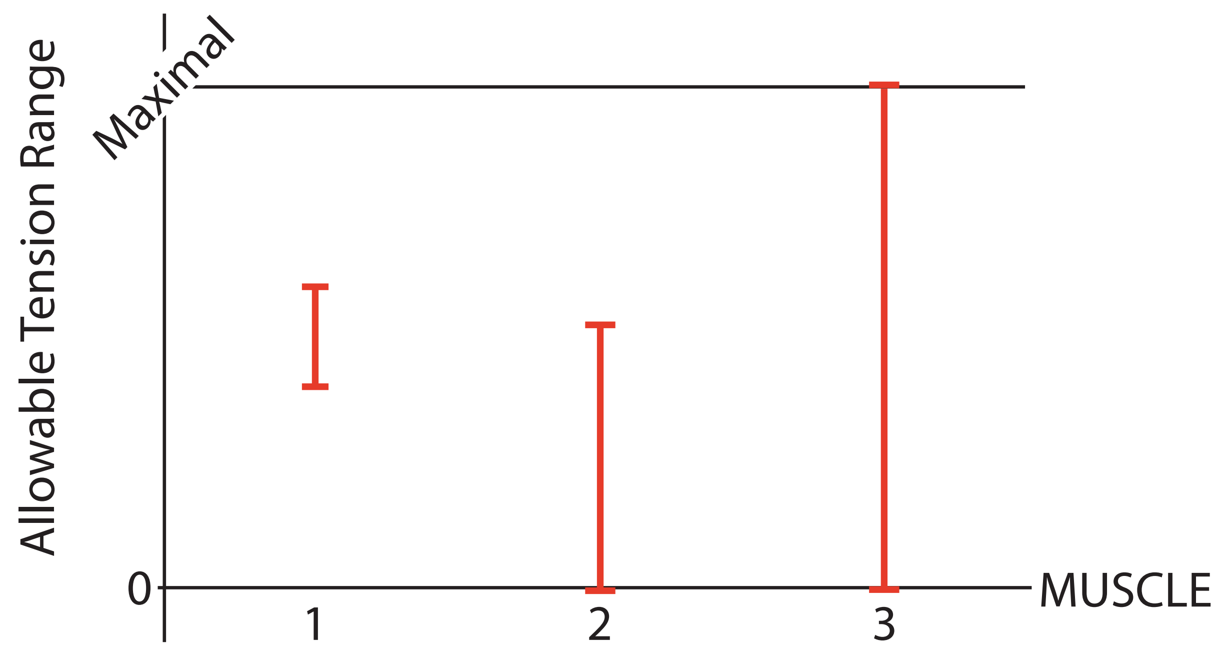

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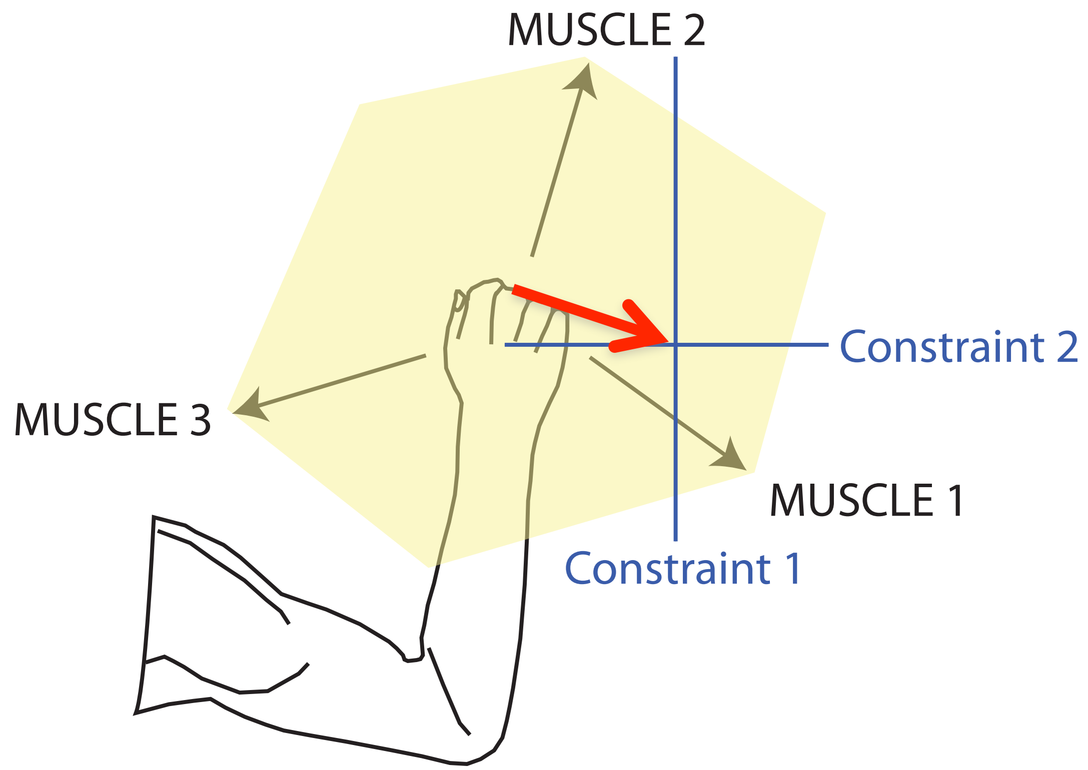

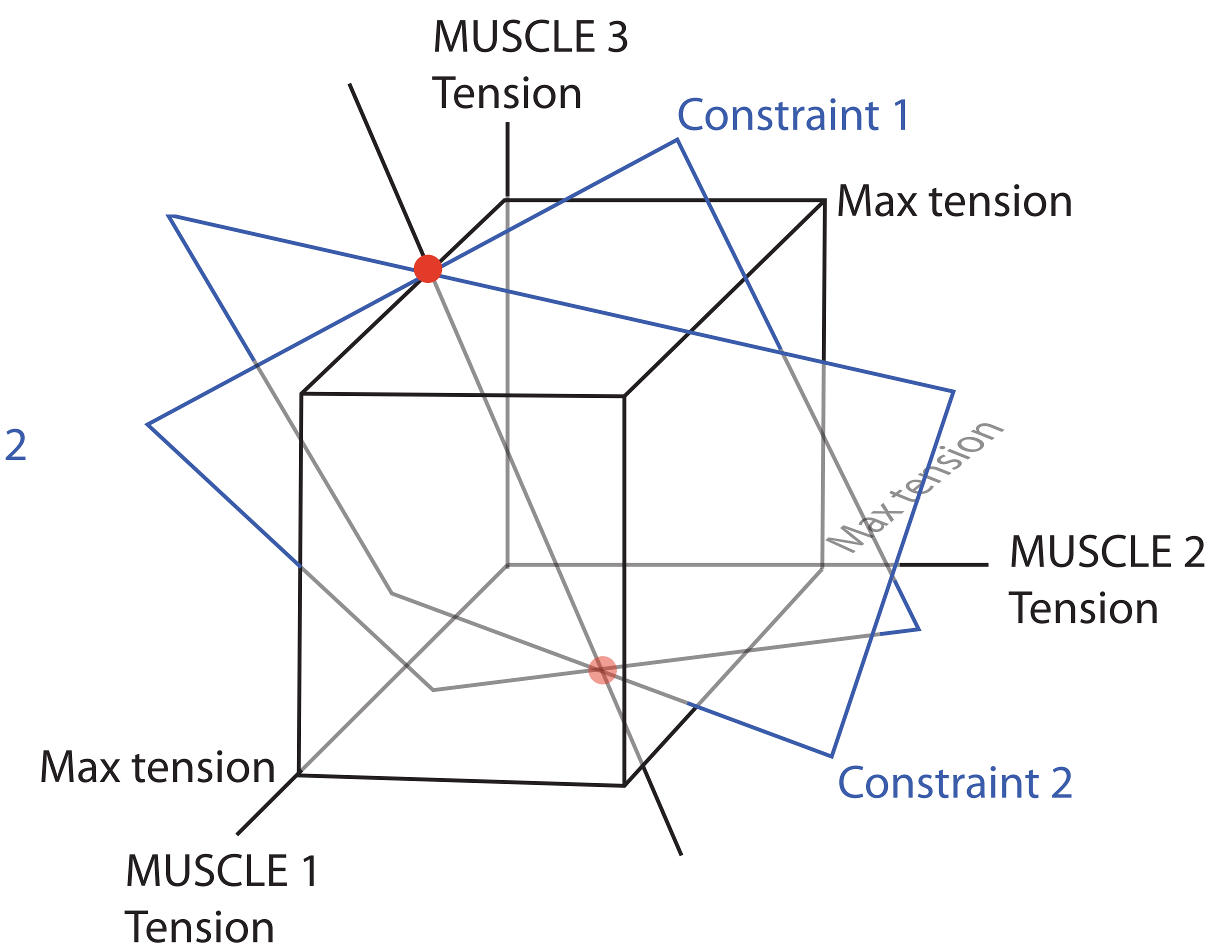

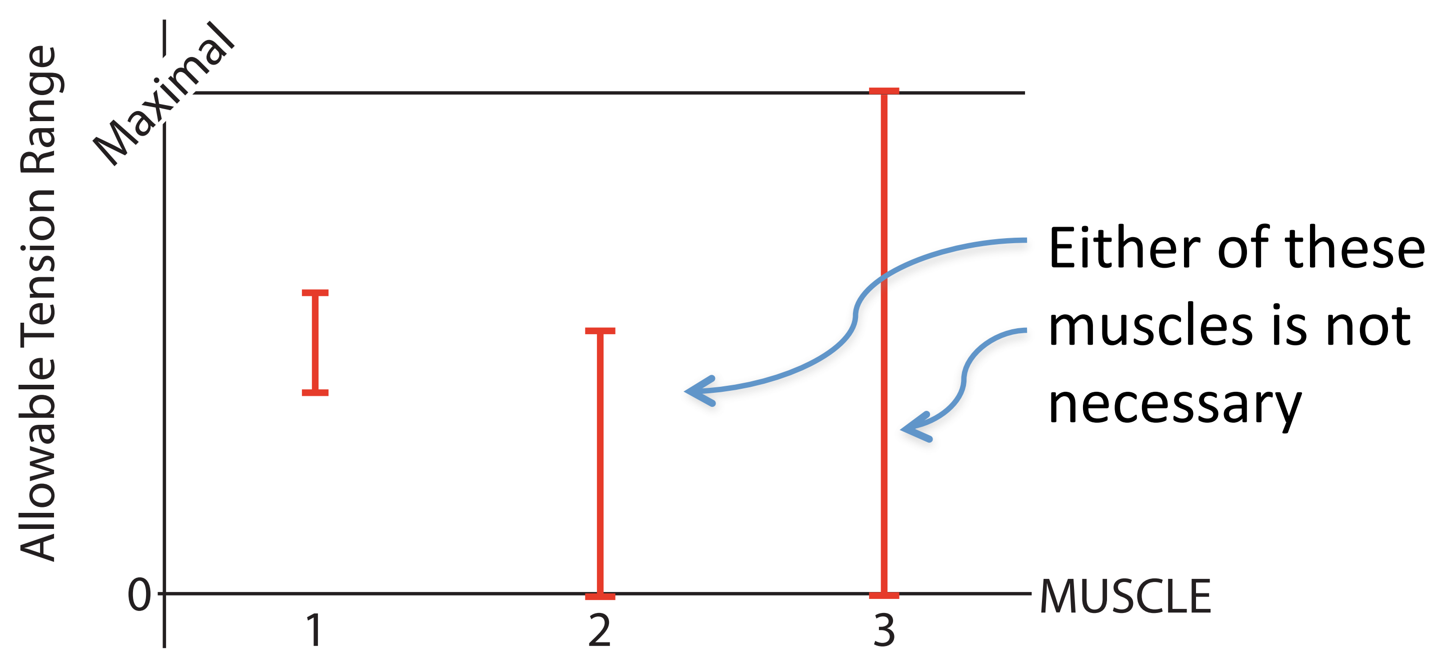

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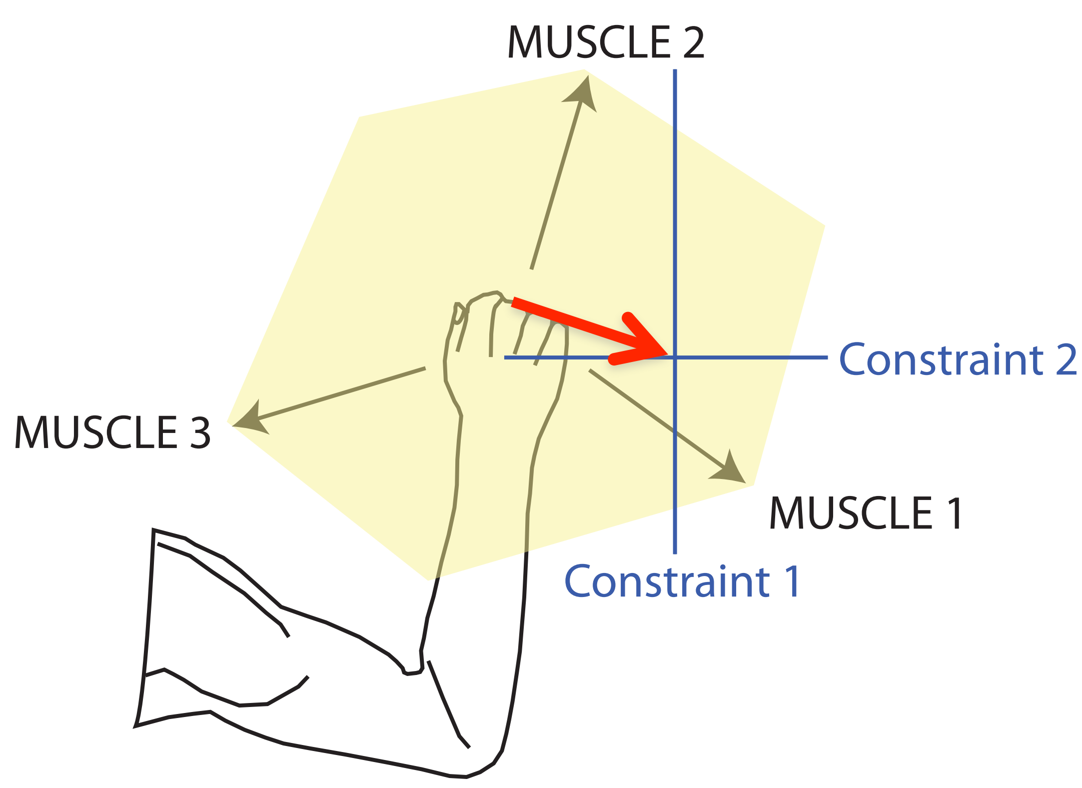
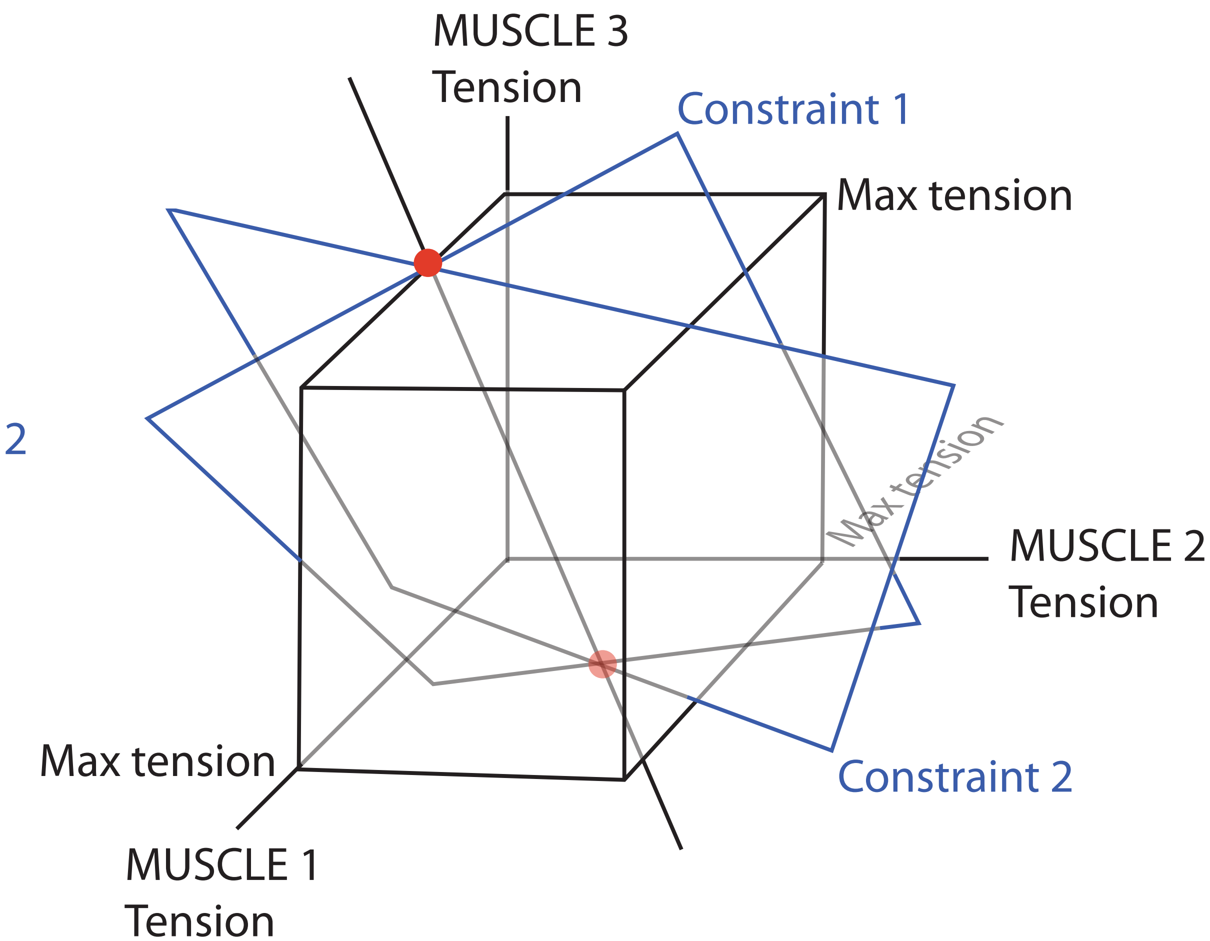
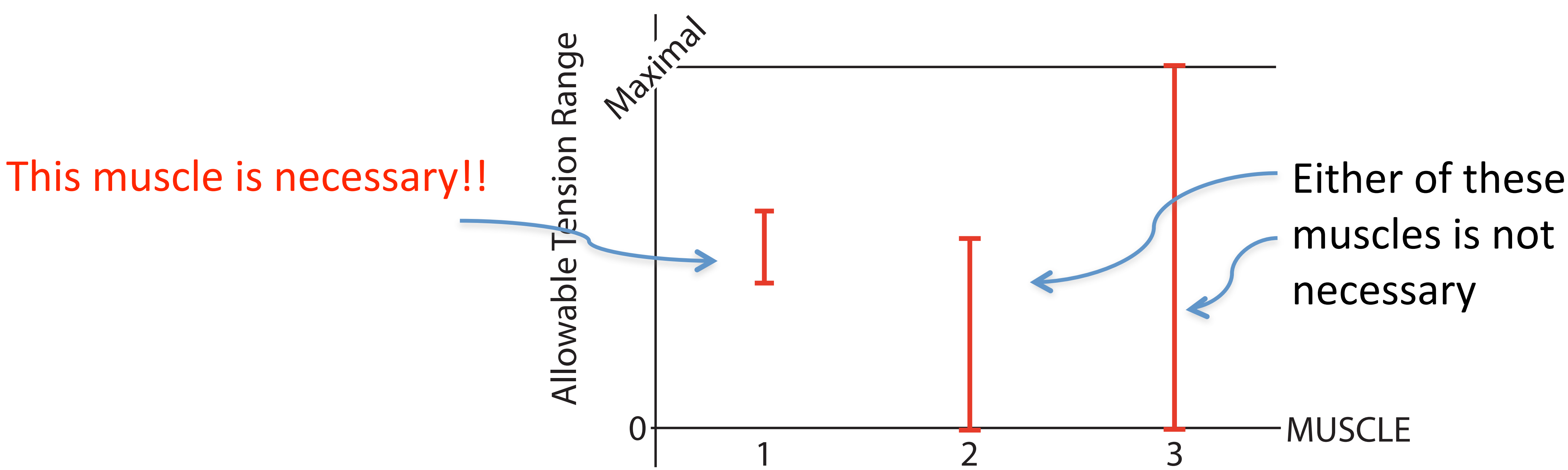


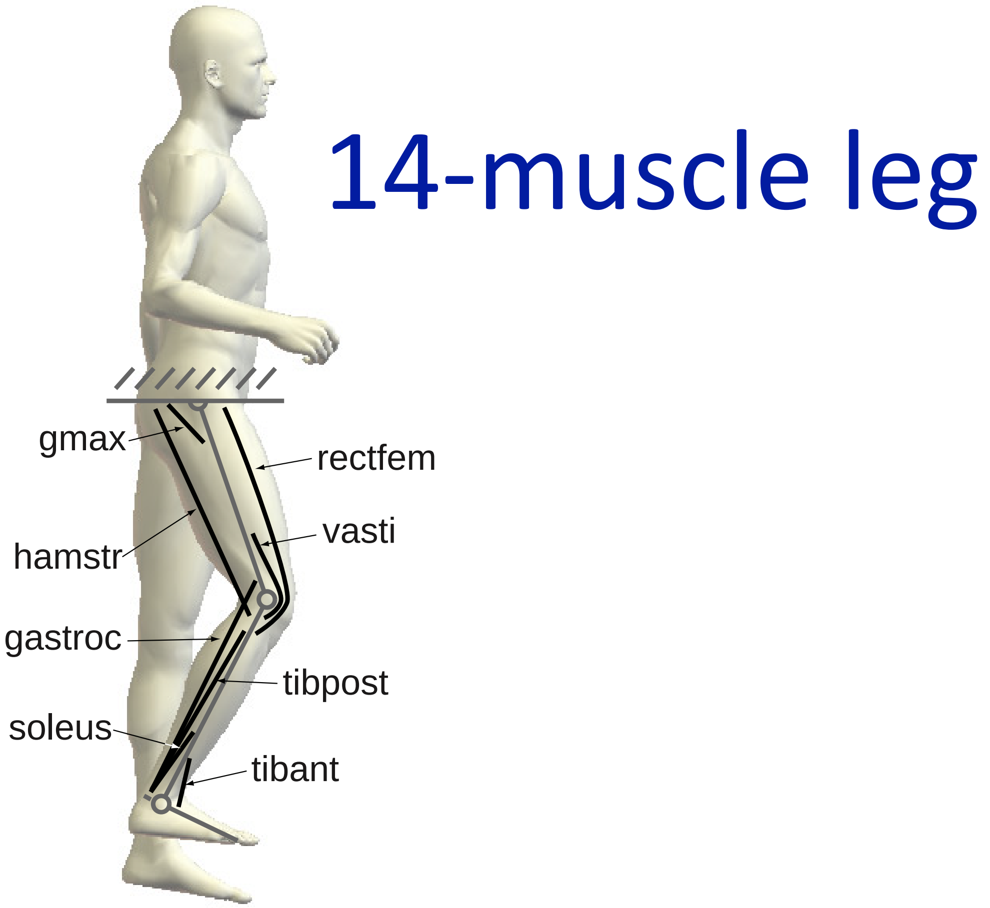




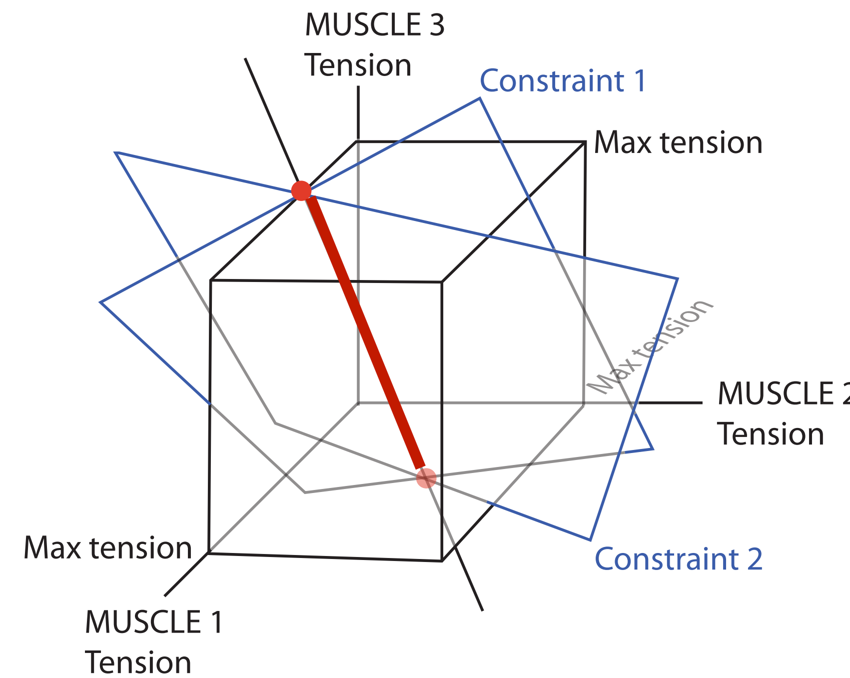
Bounding box of solution space: a gross overestimate

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011

Solution space for 14 muscles and M constraints



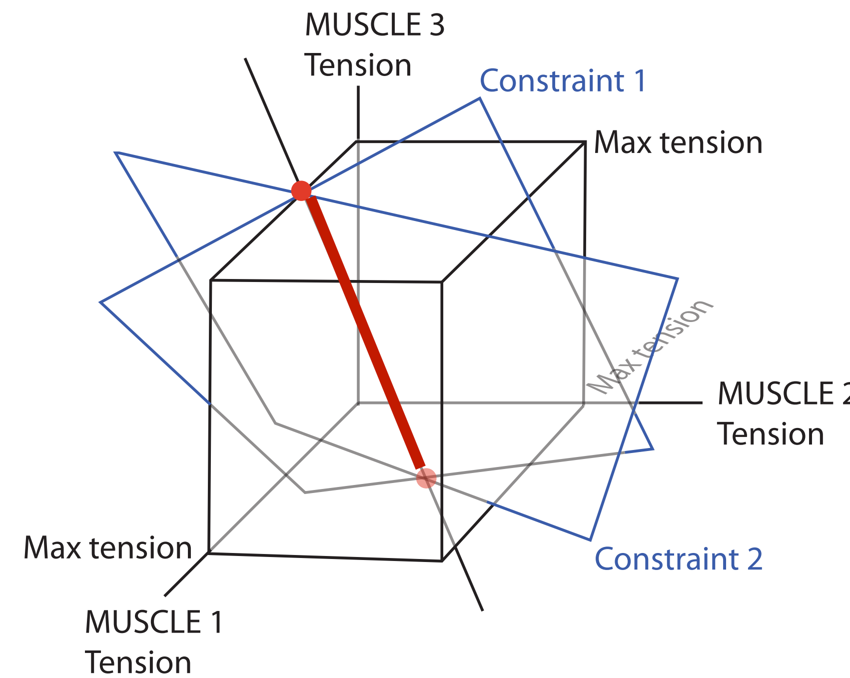
Sagittal Plane
Leg Model



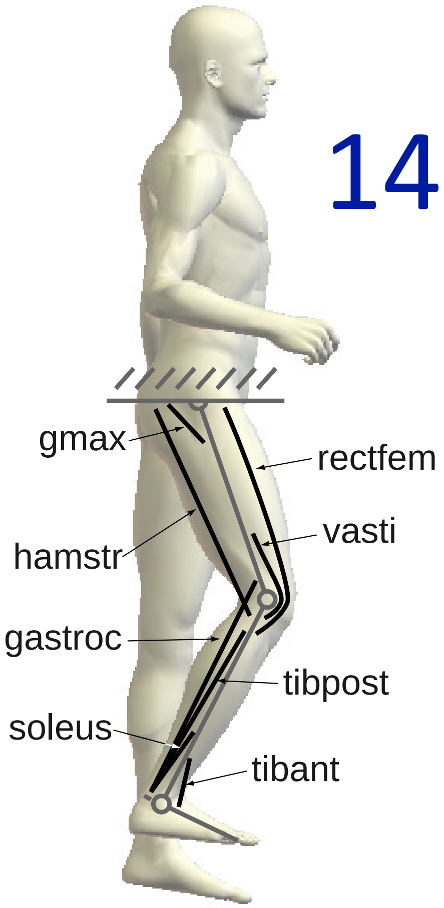
Valero-Cuevas et al., 1998, 2005, 2009; Kutch & Valero-Cuevas, Inouye and Valero-Cuevas 2011

Solution space for 14 muscles and M constraints

The solution space is a low-dimensional subset of $\mathbb{R}^{14}$ of dimension 14-M



14-muscle leg



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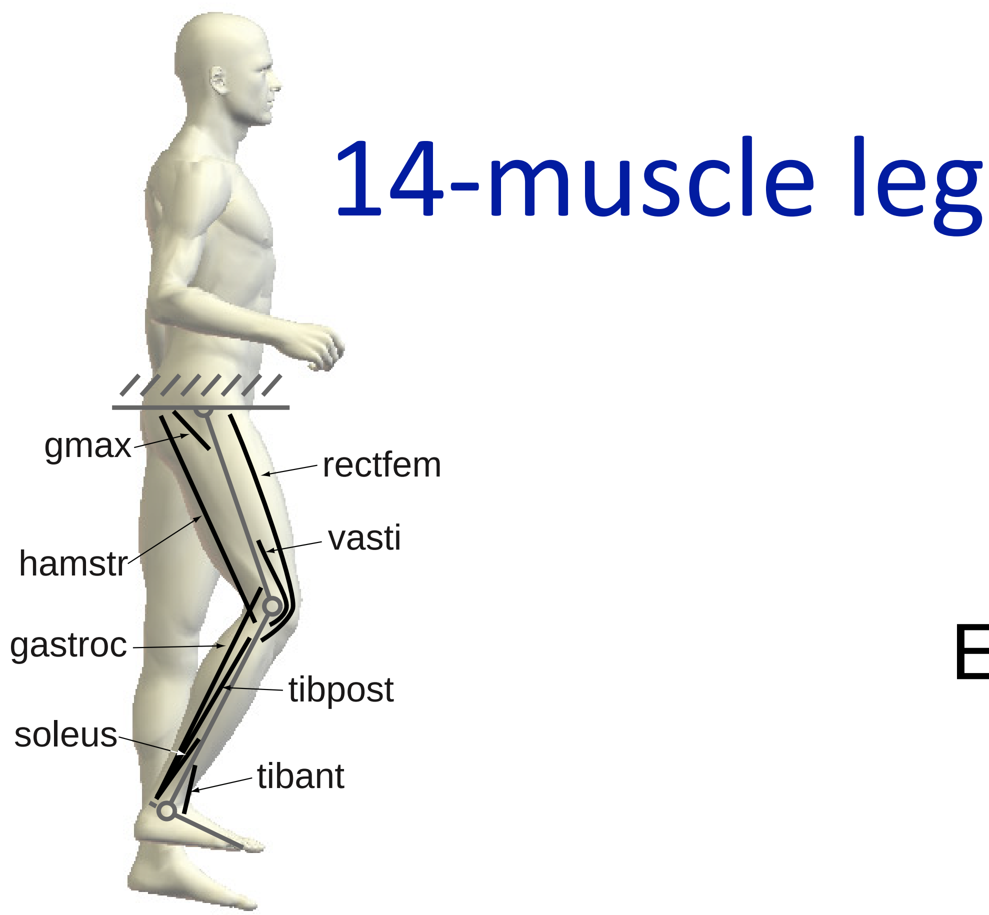

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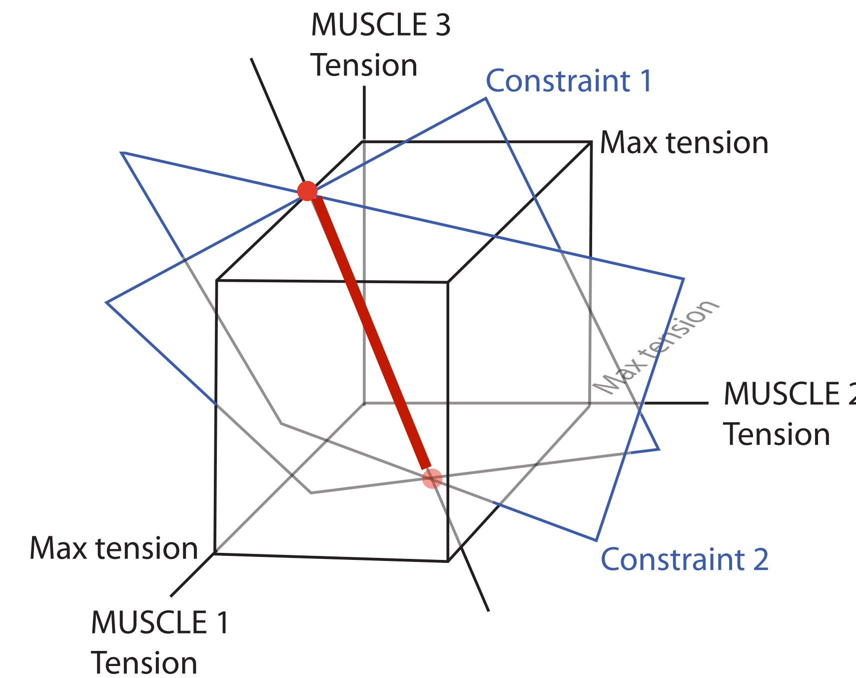

<u>Sample constraints for a real-world task</u>

Endpoint wrench magnitude and direction: 6

Leg stiffness in 3 of 6 directions: 3

Energetic cost: 1

Total: 10

Valero-Cuevas et al., 1998, 2005, 2009; Kutch & Valero-Cuevas, Inouye and Valero-Cuevas 2011

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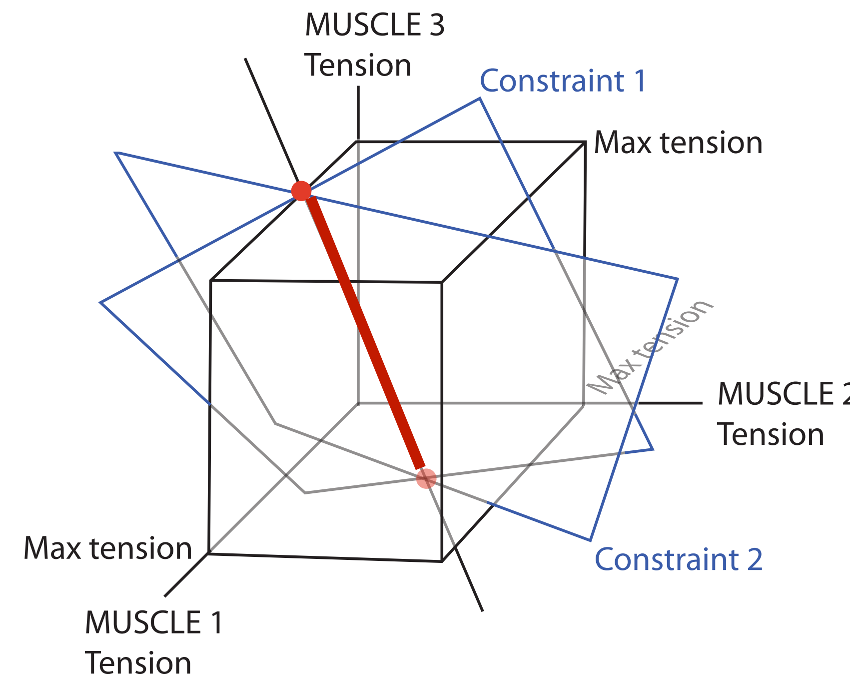

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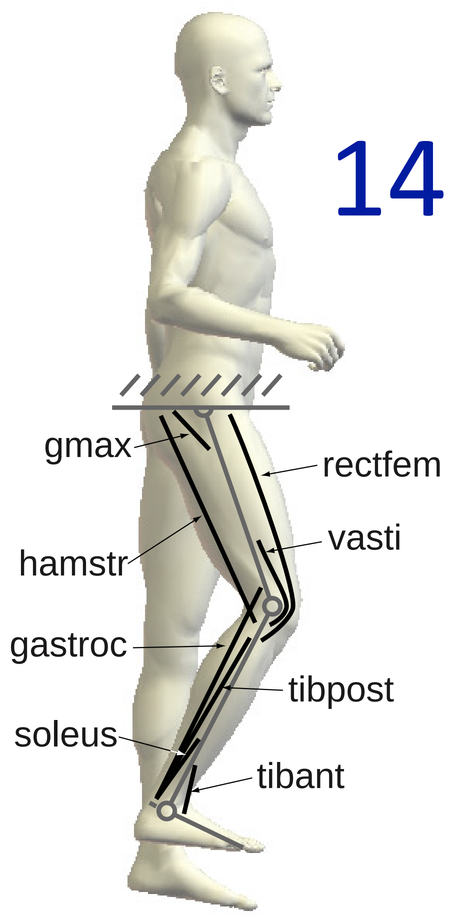

Sagittal Plane
Leg Model

<u>Sample constraints for a real-world task</u>

Endpoint wrench magnitude and direction: 6

Leg stiffness in 3 of 6 directions: 3

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The main idea is that constraints compound quickly for real-world tasks. The solution space would be a very well defined 4-D object in $\mathbb{R}^{14}$.

Valero-Cuevas et al., 1998, 2005, 2009; Kutch & Valero-Cuevas, Inouye and Valero-Cuevas 2011

I am not saying that mathematical redundancy does not exist

- After all, a line has an infinite set of points.
- But I am saying that the solution space has a very well defined structure given by the anatomy of the hardware, and the constraints of the task. Any family of valid solutions will exhibit correlations.
- …Thus if you measure muscle activity during meaningful tasks you will invariably see a reduction in dimensionality.
- The question is not whether the muscle activity will be low-dimensional or not. This is expected. The question is how the nervous system inhabits and optimizes within that reduced solution space.

Valero-Cuevas et al., 1998, 2005, 2009; Kutch & Valero-Cuevas, Inouye and Valero-Cuevas 2011

Synergies: structured covariation among variables of interest

Don’t be confused by the many definitions of synergies. E.g.,

Covariation of joint angles

Covariation of muscle activations

Covariation of finger forces

etc.

First ask yourself what covariation is being considered, and then where it comes from, and what it means.

Neural Synergies

Definition: Co-variation of muscle activation to simplify control of redundant muscles.

When can muscle synergies be attributed to the nervous system vs. mechanics?

OPEN ACCESS Freely available online

PLoS COMPUTATIONAL BIOLOGY

Challenges and New Approaches to Proving the Existence of Muscle Synergies of Neural Origin

Jason J. Kutch[1], Francisco J. Valero-Cuevas[1,2]*

2012

Summary about redundancy

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

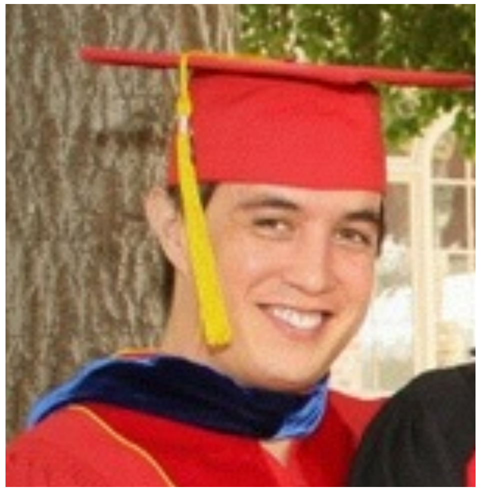
From the structure of the solution space we now see:

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

So… if you could define the tendon paths, how would you do it?
Why insists on the 2N design?

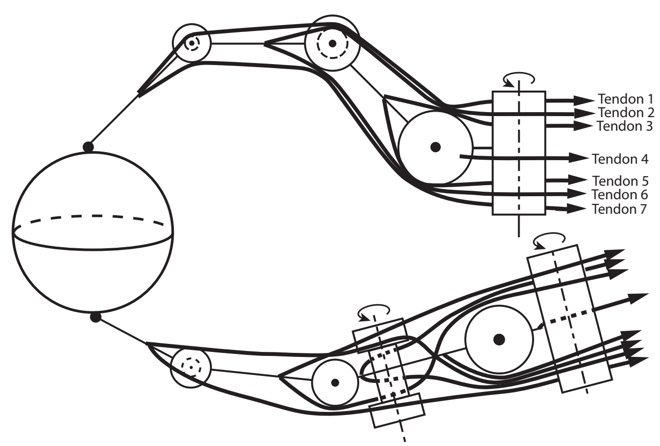
With Josh Inouye

currently post-doc at UVA



The International Journal of Robotics Research (IJRR), Special Issue on Mechanics and Design of Robotic Hands, 2013

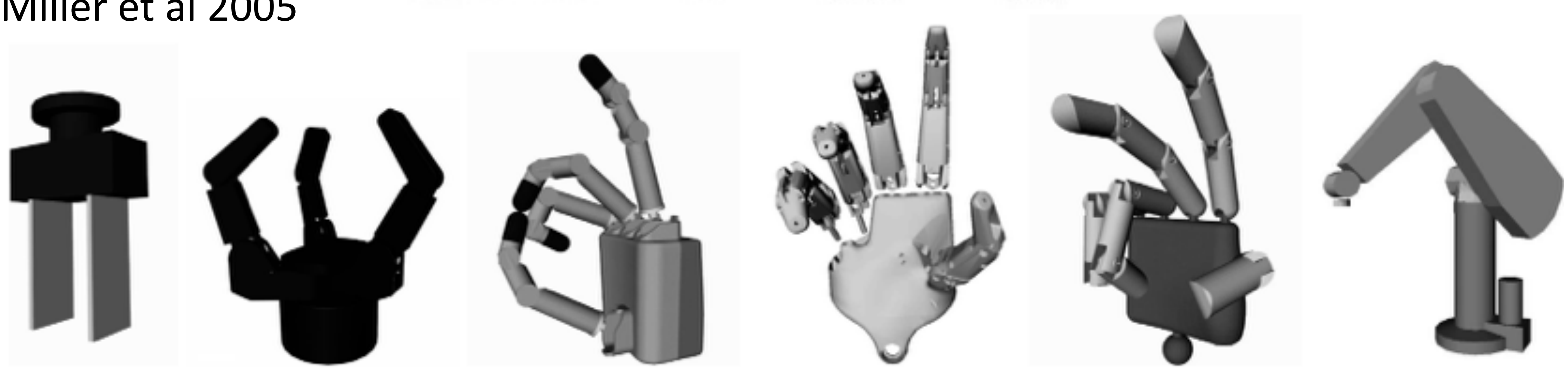
An Optimized Solution to the Grasping Problem: the Fitness of the Human Hand



Shadow Hand

Porter and Lemon 1993

Miller et al 2005



Questions

- **Is the human hand particularly well adapted** for grasp capabilities?
- How good are **naïve designs** of anthropomorphic robotic hands at grasping?
- How much can robotic hand grasping capabilities be improved **using bio-inspired characteristics**?

Grasp Quality Computation Methodology

IEEE TRANSACTIONS ON ROBOTICS

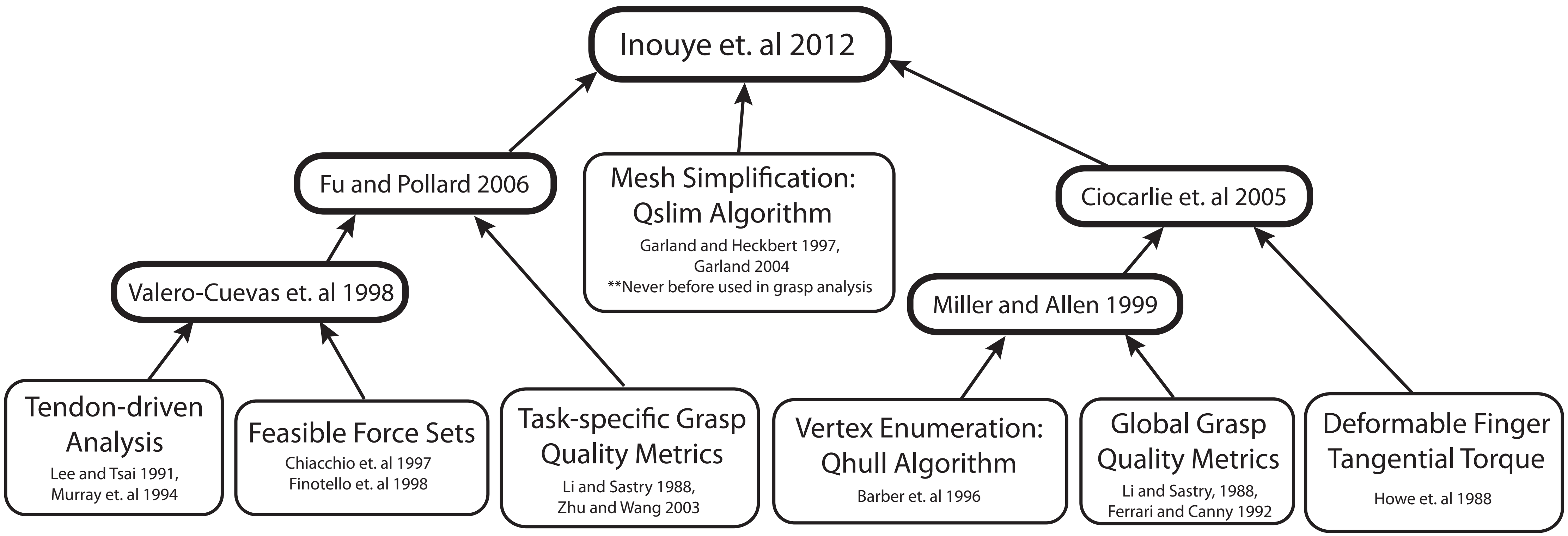
Short Papers

A Novel Synthesis of Computational Approaches Enables Optimization of Grasp Quality of Tendon-Driven Hands

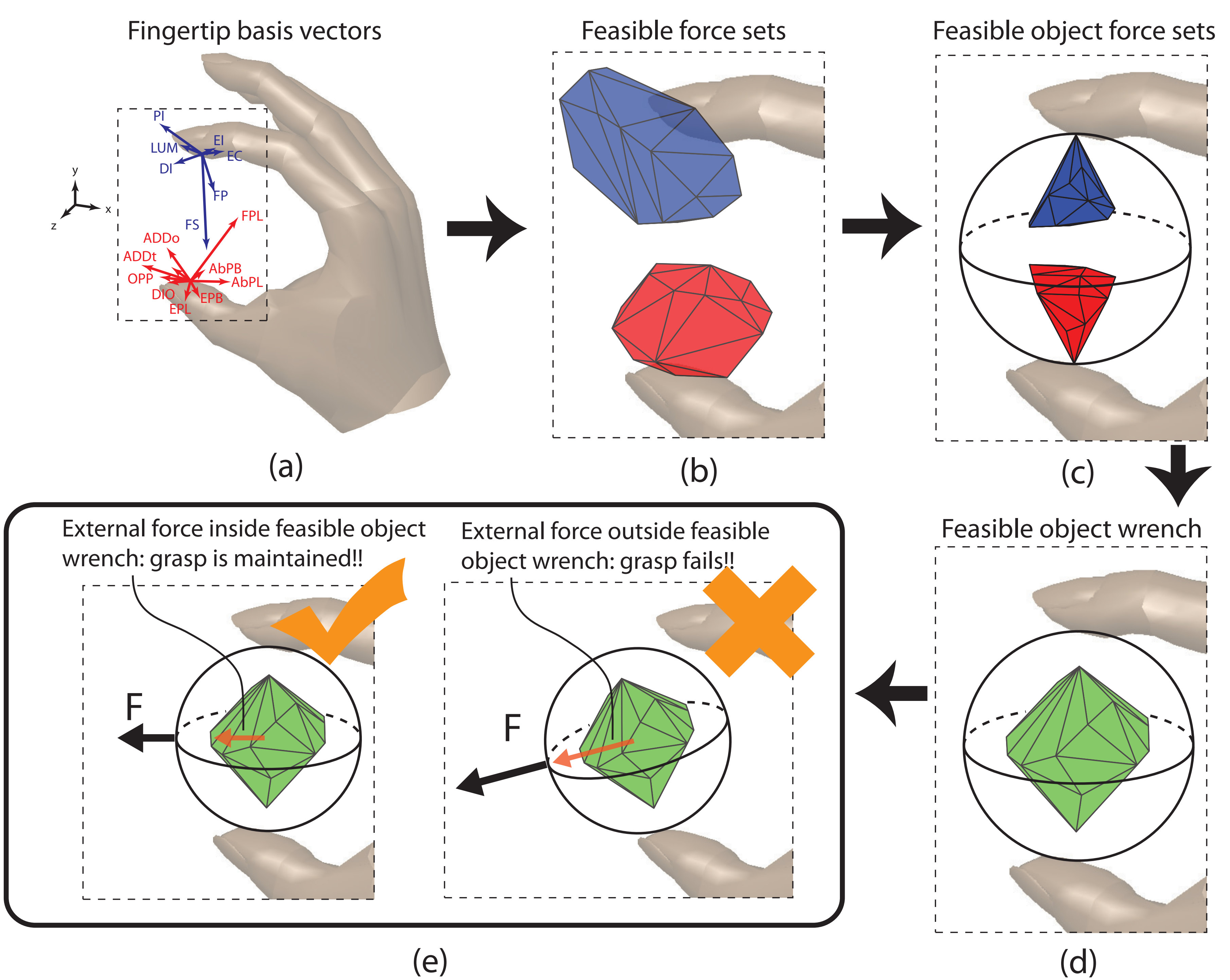
Joshua M. Inouye, Jason J. Kutch, and Francisco J. Valero-Cuevas

***Abstract*—We propose a complete methodology to find the full set of feasible grasp wrenches and the corresponding wrench-direction-independent grasp quality for a tendon-driven hand with arbitrary design parameters. Monte Carlo simulations on two representative designs combined with multiple linear regression identified the parameters with the greatest potential to increase this grasp metric. This synthesis of computational approaches now enables the systematic design, evaluation, and optimization of tendon-driven hands.**

Grasp Quality Computation Methodology

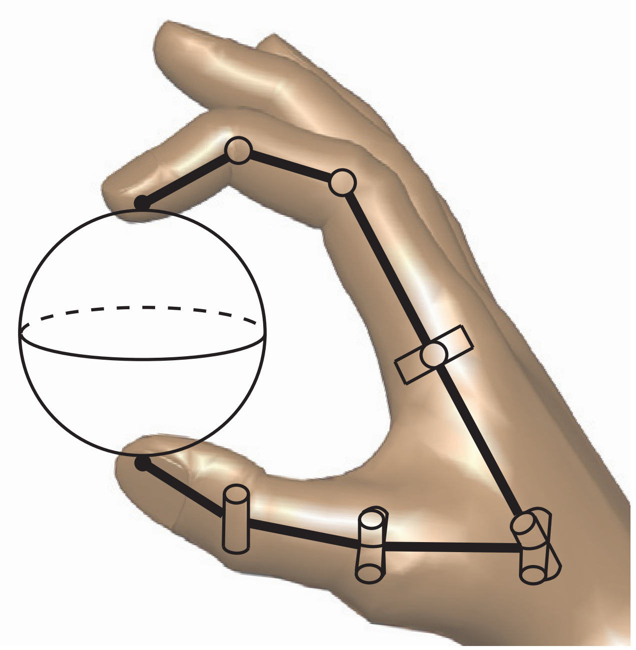


Grasp Quality Computation Methodology



A "fair" comparison between human and robotic hands

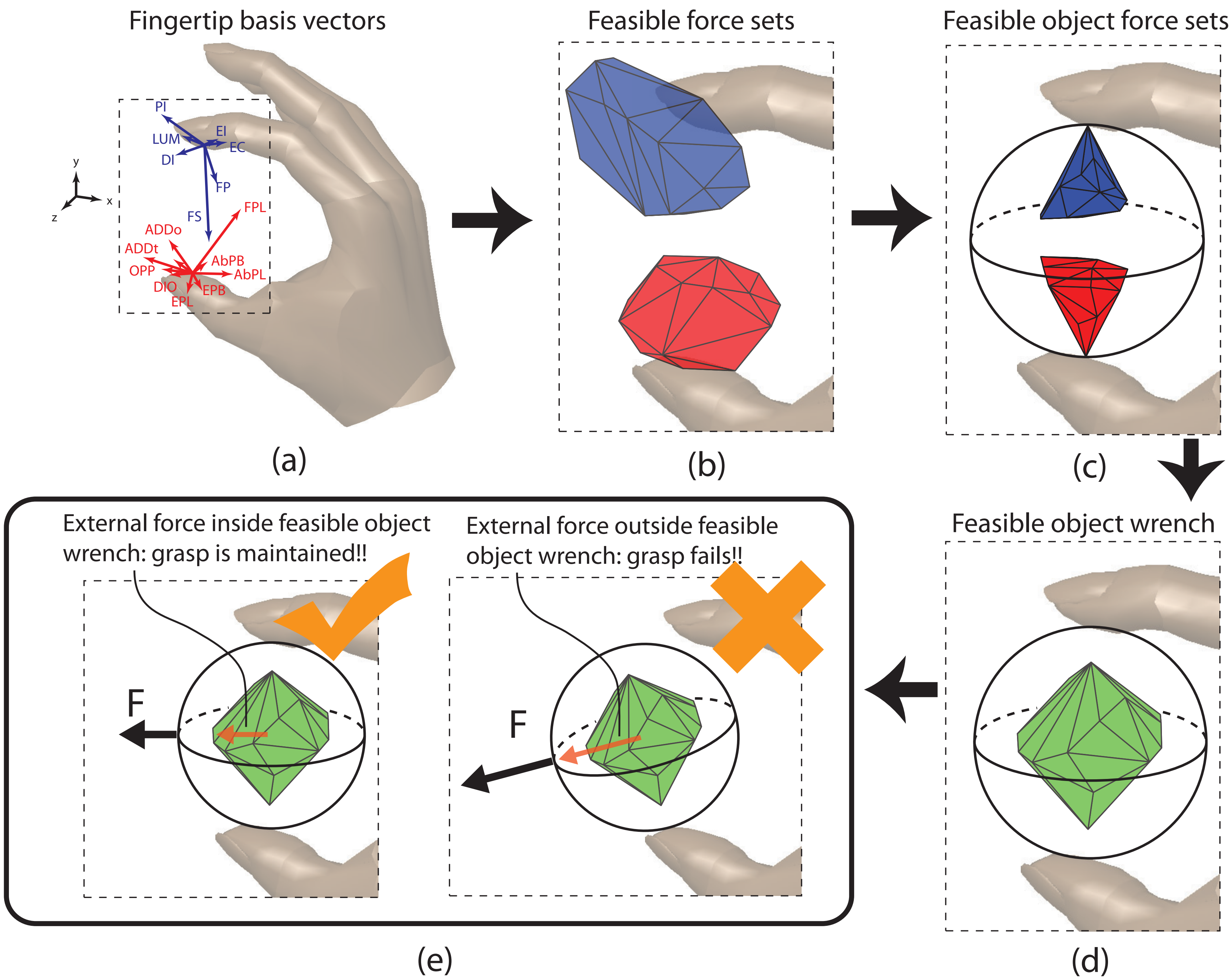
- **Shadow Hand anthropometry**
- **Same sum of maximal tendon tensions for each finger** (764N for index finger, 478N for thumb: Valero-Cuevas et al. 2000, Pearlman et al. 2004)
- **Same fingertip minimum force production capability in all directions** (2.89N for index finger, 5.37N for thumb: Valero-Cuevas et al. 2000, Pearlman et al. 2004)
- **Same joint diameters**: Valero-Cuevas et al. 1998 and 2003



Joint		Joint Diameter (mm)
Index finger	MCP Adduction-Abduction	10.9
	MCP Flexion-extension	21.0
	PIP Flexion-extension	9.25
	DIP Flexion-extension	5.14
Thumb	CMC Adduction-Abduction	35.6
	CMC Flexion-extension	40.4
	MP Adduction-Abduction	15.5
	MP Flexion-extension	20.2
	IP Flexion-extension	11.0

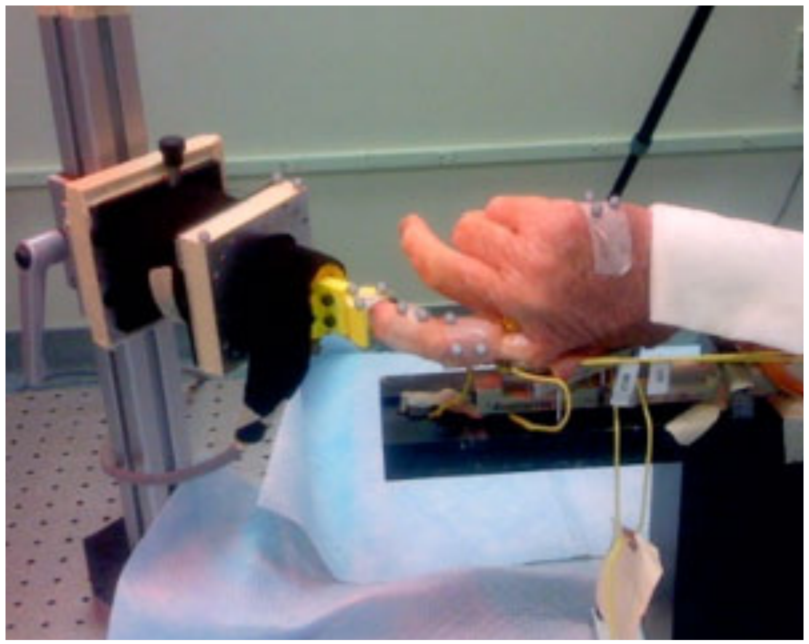
IJRR 2014

Grasp Quality Computation Methodology

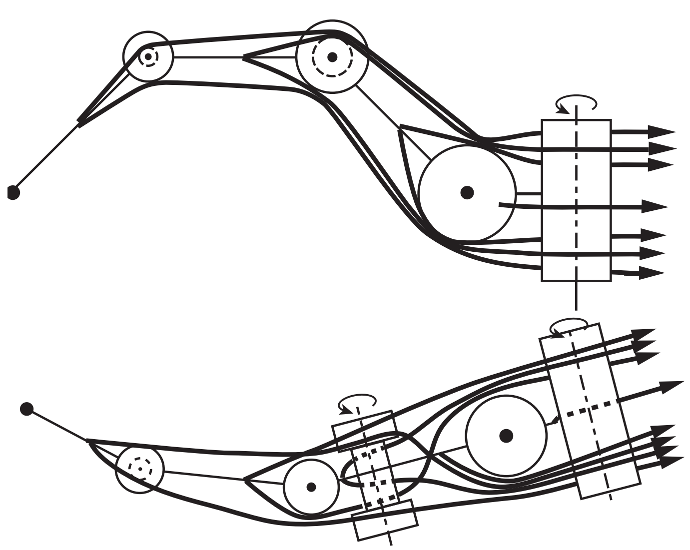


Grasp Quality Computation Methodology

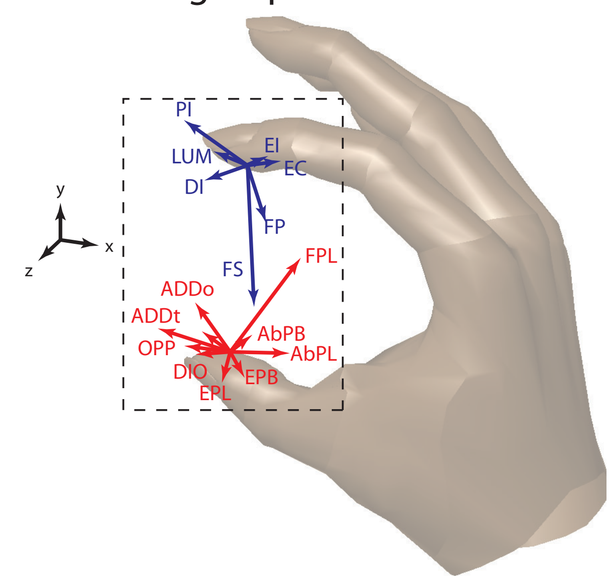
Human hand: from cadaver measurements



Robotic hand: from analytical solution

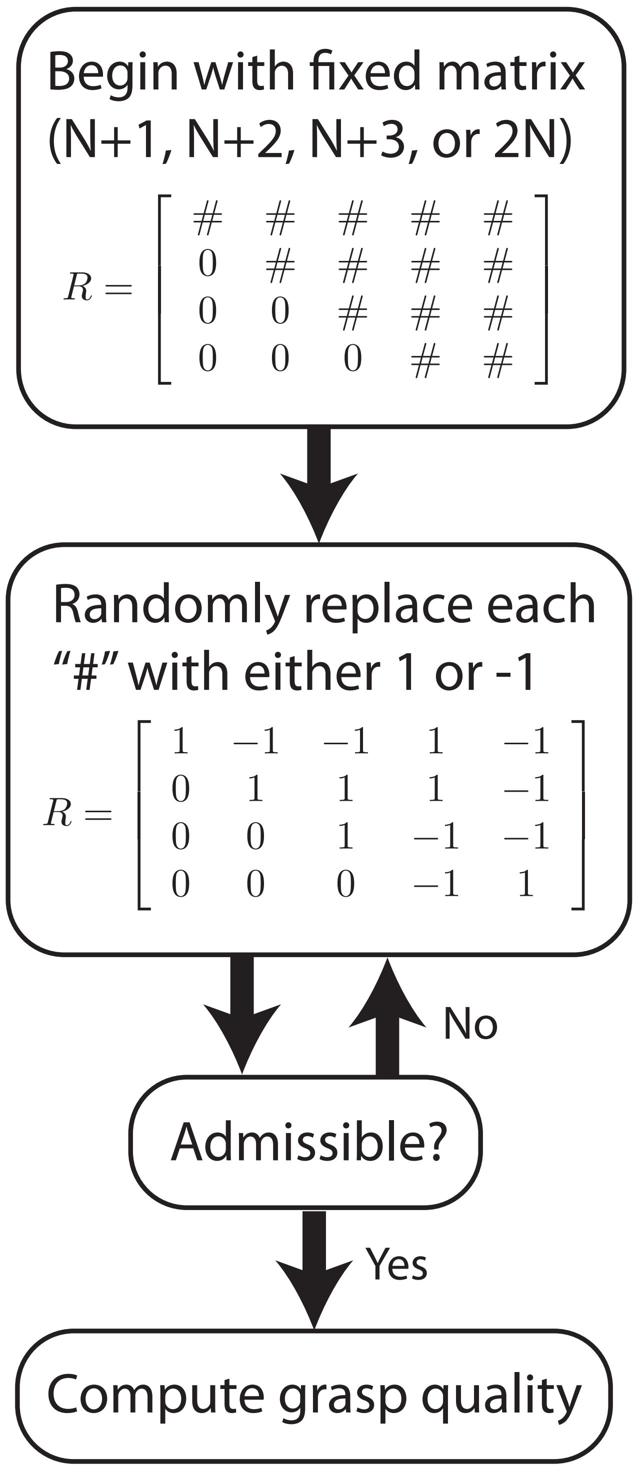


Fingertip basis vectors

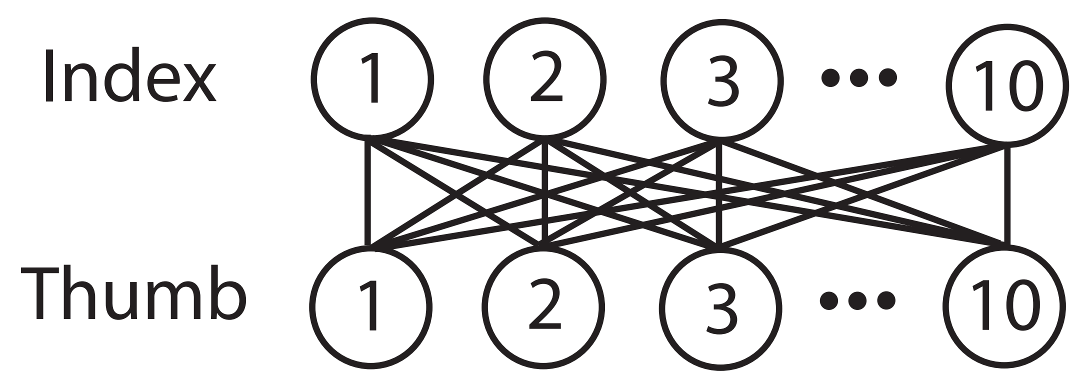


Methods: Analytical solution

Monte Carlo search on moment arm matrices



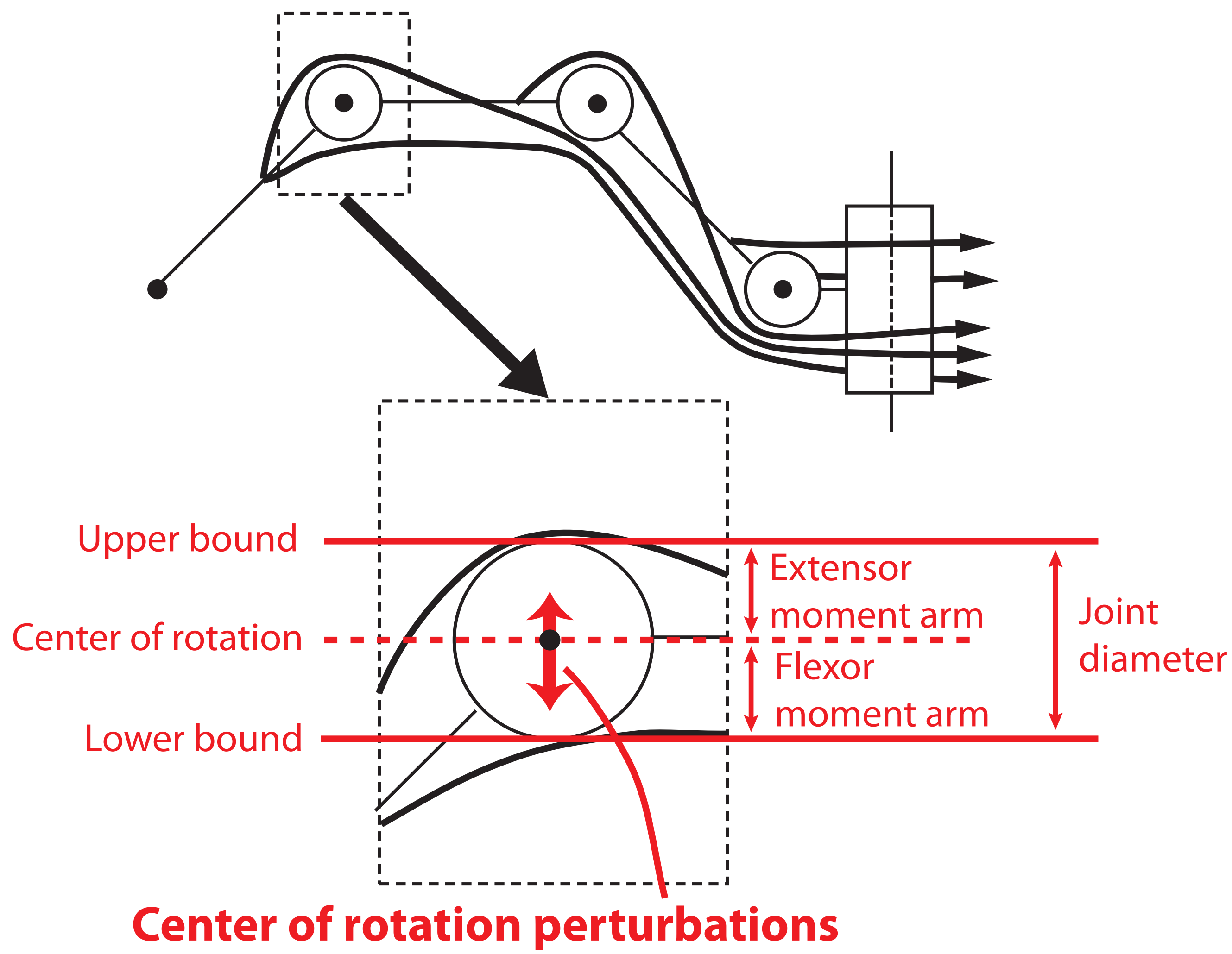
Crossover of best (highest force production in all directions) moment arm matrices (similar to genetic algorithm process)



Methods

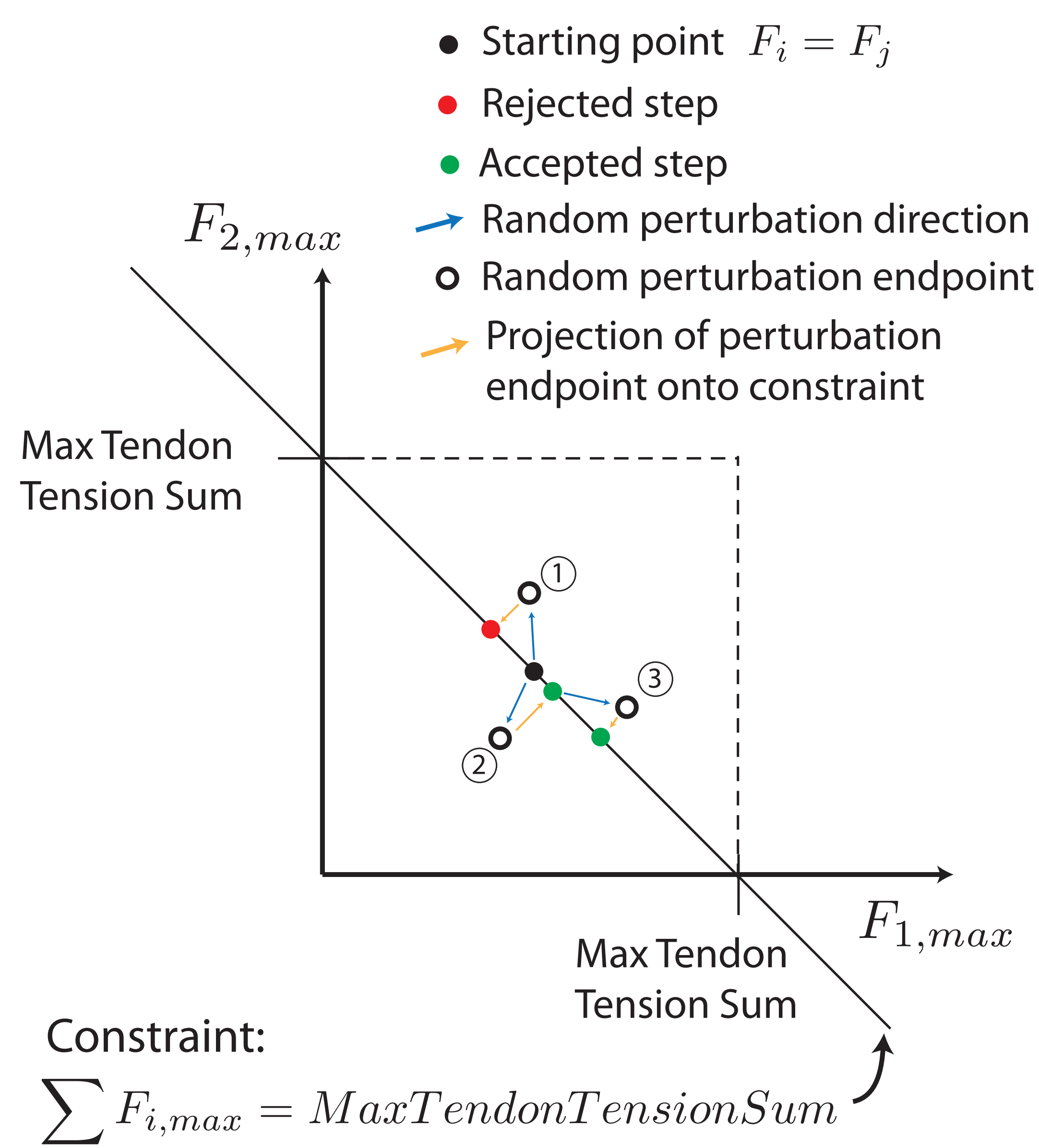
Step #1

Center of rotation random search (Greedy Markov-Chain Monte Carlo)

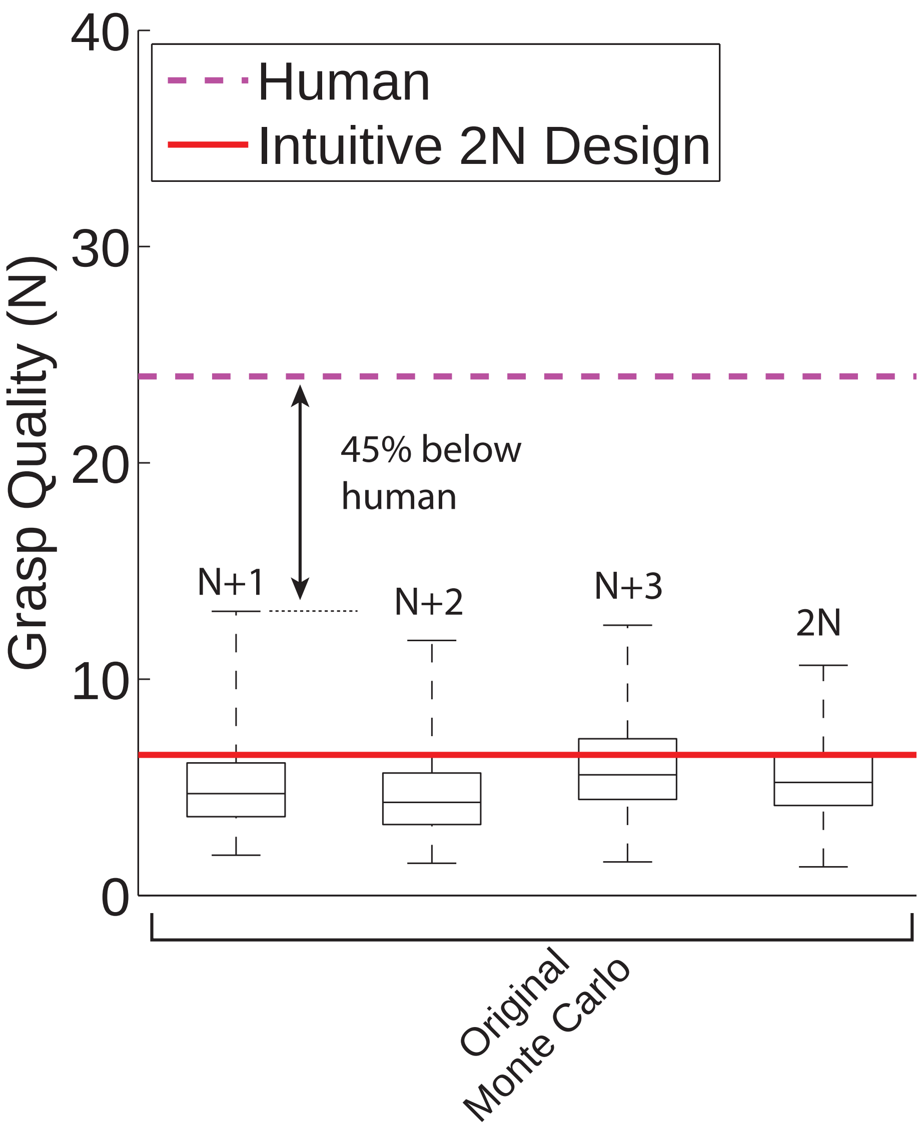


Step #2

Maximal tendon tension distribution random search (also MCMC)

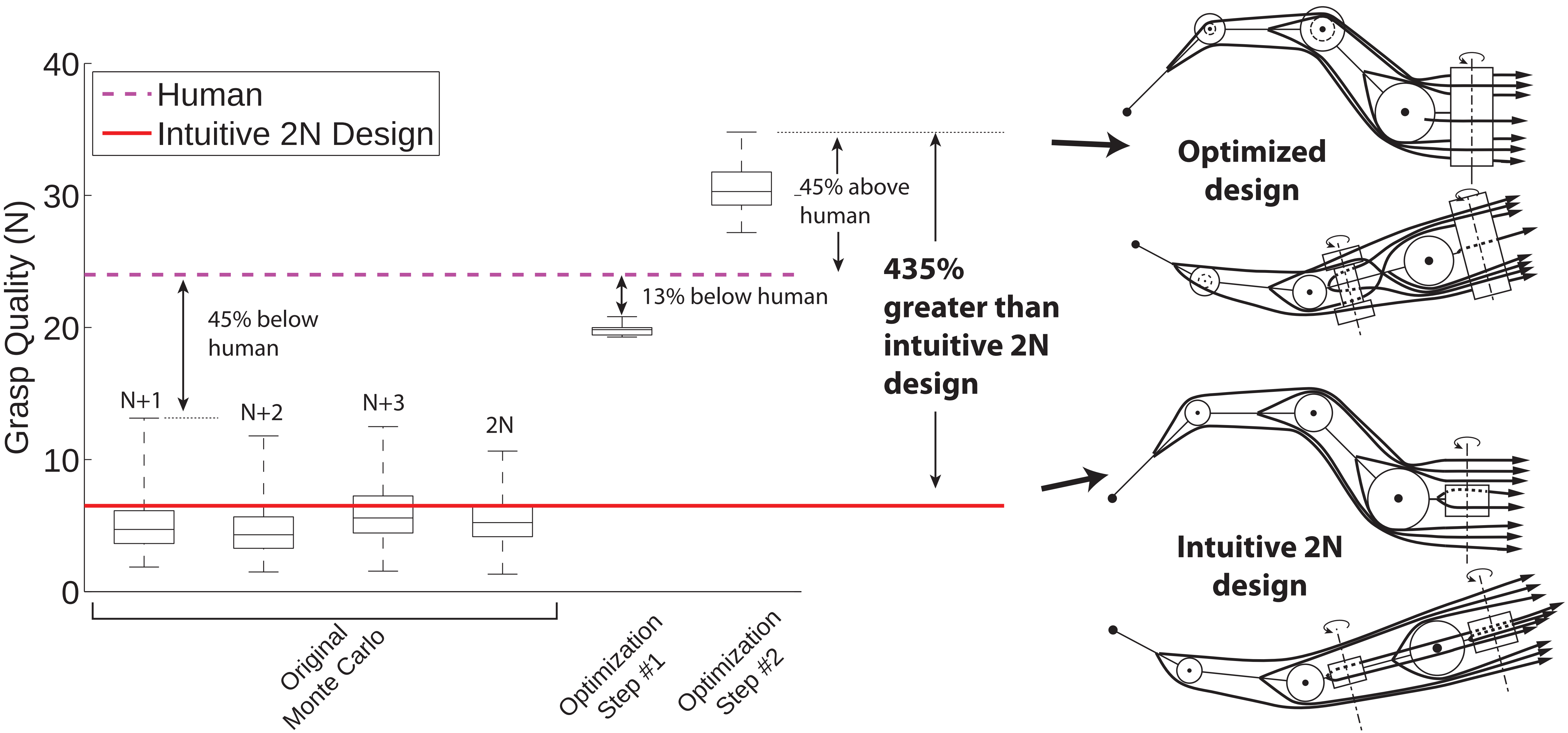


Results



The International Journal of Robotics Research (IJRR), Special Issue on Mechanics and Design of Robotic Hands, 2013

Results



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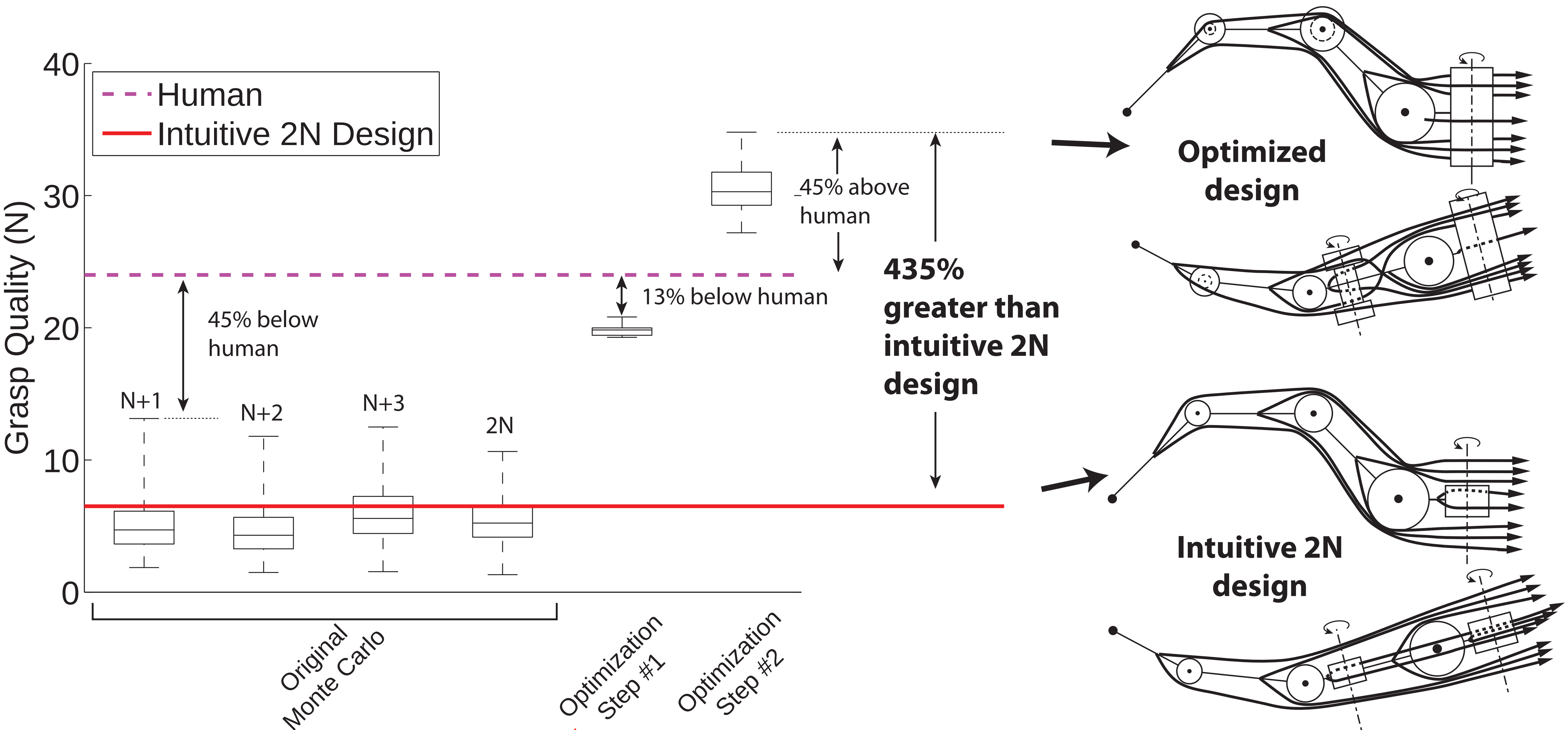
Results



Center of Rotation

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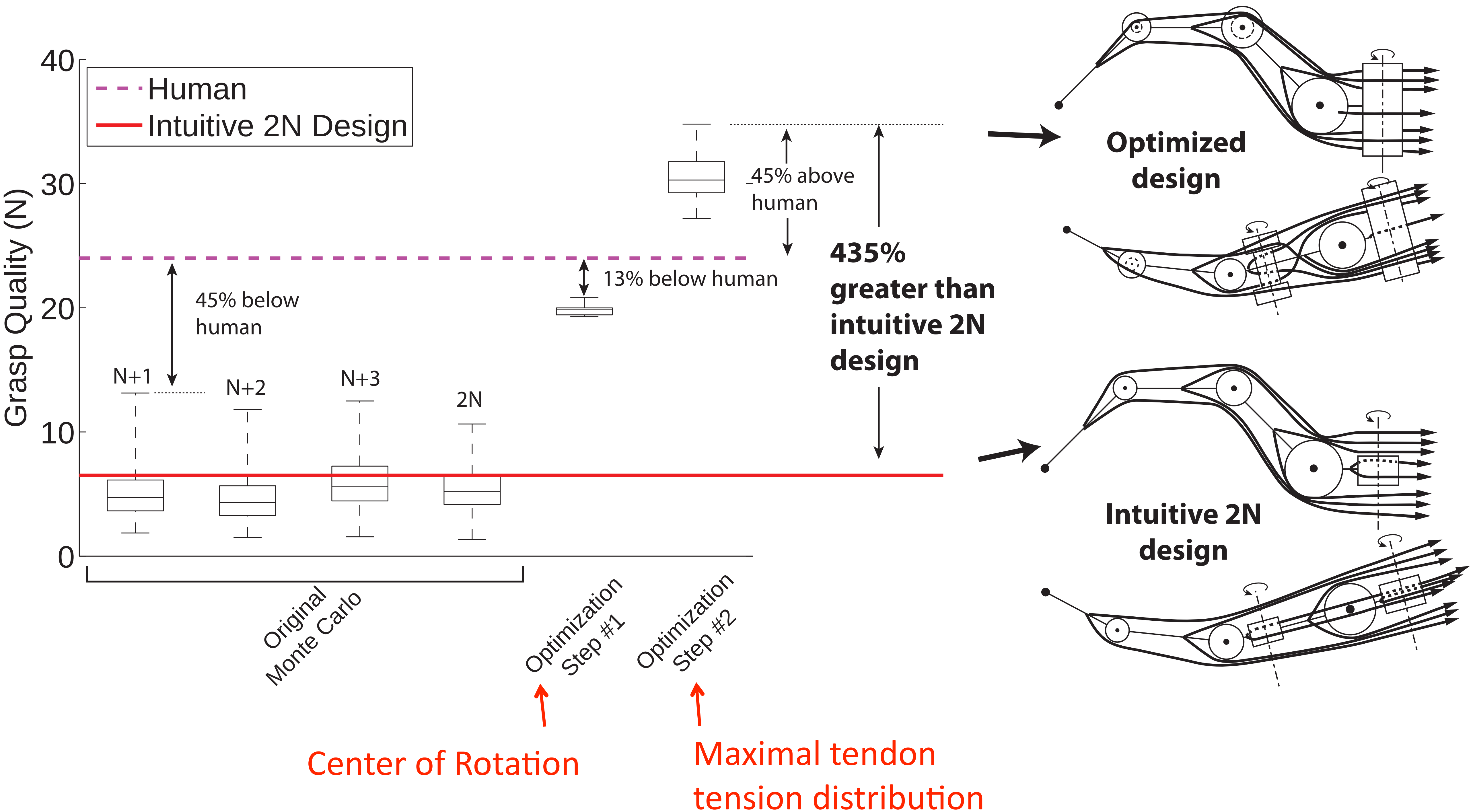
Results



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Conclusions about design of tendon-driven systems

- The human hand has **critical morphological features** lending it very good grasp capabilities.

- The **grasping capabilities** of robotic hands can be **drastically improved** by exploring the full design space
  - Non-uniform maximal tendon tension distributions
  - Center of rotations not in the middle of the joint
  - Roboticists, however, tend to insist on 2N designs!

Conclusions:

- There is much good and much bad…
- If you are making tendon-driven systems: explore the design space!
- I strongly encourage you to challenge the cortico-centric view of hand control, and explore the many possibilities afforded by a distributed, hierarchical, embedded logic.
- Also, we owe much to sociobiological co-evolution of objects with our hands.
- Think of how long it took you to learn to use your hand, and how susceptible it is to dysfunction!
- I think we have barely enough degrees of freedom for natural function.
- We are not done evolving ;)

Current and recent lab members

Open post-doc positions!

Funding Sources

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Thank you