Purpose of this talk

To be informative, but also provocative, about the role of mechanics and computational science understanding the control neuromuscular systems.

Provide several examples of how mechanics has helped us understand neuroscience.

Frame computational neuromechanics as a Big Data problem.
Hot topics of the day

Muscle redundancy
Muscle Synergies
Optimization and Optimal control
Motor learning
Motor policies
Bayesian motor control
My scientific approach to these problems

Sensorimotor behavior

Theories of neural control

Machine learning

Musculoskeletal modeling

Physical modeling

Neurophysiology

Clinical and rehabilitation tools
Some long term questions

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

and/or

What specific contributions from passive (e.g., the body) and active (e.g., the brain) components enable dexterous function?
For example, computational modeling of neuromuscular systems is still in its infancy.

**Machine learning**
- *Supervised learning*
  - (Backpropagation ANNs, support vector machines)
- *Unsupervised learning*
  - (PCA, self-organized ANNs)

**Control theory**
- **Classical control**
  - (Root locus design, tracking)
- Robust Control
- Adaptive control
- Hierarchical control
- Model predictive control
- Hybrid control
- Reinforcement learning
  - (Policy gradients, Q-learning)
- *Optimal Control*
  - (LQR, LQG, iLQR, iLQG)

**Stochastic Estimation**
- (Kalman filter, extended Kalman filter)
- *Bayesian estimation*
  - (Particle filters, path integral estimation, Monte Carlo simulations)

**Estimation-Detection theory**
- Minimum variance unbiased estimation (MVUE)
- Best linear unbiased estimator (BLUE)
  - etc.

Valero-Cuevas et al., IEEE RBME 2009
The problems in motor neuroscience today

We agree on physics, mechanics, physiology, and computational principles; but the consequences of our experimental and modeling choices are hard to reconcile.

As a result, we are united by our methods but fragmented into schools of thought that tend to talk and publish past each other.

Consider the longstanding debates around topics like internal models, equilibrium point control, optimal control, synergies, etc.

Many of these debates become a matter of opinion.
The fundamental challenge for organisms: *Newton and Darwin are unforgiving*

Mechanics describes the undeniable physical reality.

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

We must move from Computational *Neuroscience* to Computational *Neuromechanics*
Where is one to begin?

From *The Help* 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 some of us

Why do we have so many muscles?
Neuromechanical Concept #0

Control of force
(underdetermined—redundancy)
vs.
Control of motion
(overdetermined—no redundancy)
Simplest tendon mechanics

Fig. 4.5 Schematic representation of the calculations of the moment arm, $r(q)$. Given tendon excursion as a function of joint angle $s(q)$, the moment arm is the partial derivative with respect to the joint angle $r(q) = \frac{ds}{dq}$, Eq. 4.9 [4].

Fig. 4.6 Measurement of tendon excursion for a simple tendon path. Note that a negative (as per the right hand rule) rotation of the joint $-\delta q$ induces a positive (rightward) tendon excursion $\delta s$ that lengthens the musculotendon, and vice versa. See Sect. 4.6 for a definition of this sign convention.

Fig. 4.7 A planar 1D OF limb driven by 6 tendons.
Force control vs. movement control

\[ \tau = r(q)^T f_m = (r(q)_1, r(q)_2, \ldots, r(q)_N)^T \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{pmatrix} \] underdetermined

\[ \begin{pmatrix} \delta s_1 \\ \delta s_2 \\ \vdots \\ \delta s_N \end{pmatrix} = \begin{pmatrix} r(q)_1 \\ r(q)_2 \\ \vdots \\ r(q)_N \end{pmatrix} \delta q \] overdetermined
Reflexes respond to tendon excursions

To lengthen a muscle…. you have to silence its stretch reflex!
Neuromechanical Concept #1

Feasible function vs. Optimal function

for underdetermined systems
Muscle redundancy as the central problem of motor control.

Popular View:
We have many more muscles than kinematic degrees of freedom.

This allows infinite solutions.

Therefore the nervous system 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?
This book provides a conceptual and computational framework to study how the nervous system exploits the anatomical properties of limbs to produce mechanical function. The study of the neural control of limbs has historically emphasized the use of optimization to find solutions to the muscle redundancy problem. That is, how does the nervous system select a specific muscle coordination pattern when the many muscle of a limb allow for multiple solutions? I revisit this problem from the emerging perspective of neuromechanics that emphasizes finding and implementing families of feasible solutions, instead of a single and unique optimal solution. Those families of feasible solutions emerge naturally from the interactions among the feasible neural commands, anatomy of the limb, and constraints of the task. Such alternative perspective to the neural control of function is not only biologically plausible, but sheds light on the most central tenets and debates in the fields of neural control, robotics, rehabilitation, and brain-body co-evolutionary adaptations. This perspective developed from courses I taught to engineers and life scientists at Cornell University and the University of Southern California, and is made possible by combining fundamental concepts from mechanics, anatomy, robotics and neuroscience with advances in the field of computational geometry.

Fundamentals of Neuromechanics is intended for neuroscientists, roboticists, engineers, physicians, evolutionary biologists, athletes, and physical and occupational therapists seeking to advance their understanding of neuromechanics. Therefore, the tone is decidedly pedagogical, engaging, integrative and practical to make it accessible to people coming from a broad spectrum of disciplines. I attempt to tread the line between making the mathematical exposition accessible to life scientists, and convey the wonder and complexity of neuroscience to engineers and computational scientists. While no one approach can hope to definitively resolve the important questions in these related fields, I hope to provide you with the fundamental background and tools to allow you to contribute to the emerging field of neuromechanics.

http://valerolab.org/fundamentals

All lectures are available online
Free e-Book at universities with SpringerLink
How did this paradox arise?

The brain is confronted with controlling muscles and tendons system, yet for mathematical and technical convenience (both very good reasons!) we have historically phrased the problem as one of torque control or of simplified musculature.

Much of what I have learned has come from using and extending techniques to study the mechanics of tendon-driven systems.
What is a limb?
What is limb function?

Brain

Spinal cord

Muscles, bones and joints

Motor Cortex

Motor Neuron

Flexor

Extensor
The musculo-skeletal system “filters” the propagation of neural commands

- **Input**
  - Muscle activation
    - (activation space)

- **Muscles**
  - Muscle force
    - (muscle force space)

- **Tendons & joints**
  - Joint torques
    - (torque space)

- **Bones**
  - Endpoint forces and torques
    - (wrench space)

- **Motor Cotex**

- **Motorneuron**

- **Flexor**

- **Extensor**

Block diagram of transformations in a forward limb model.
The musculo-skeletal system “filters” the propagation of neural commands

Input
- Muscle activation (activation space)

Muscles
- Muscle force (muscle force space)

Motor Cortex

Motorneuron

Tendons & joints
- Joint torques (torque space)

Bones

Extensor

Flexor

Output
- Endpoint forces and torques (wrench space)
The musculo-skeletal system “filters” the propagation of neural commands

Muscle activation (activation space) → Muscles → Tendons & joints → Bones → Endpoint forces and torques (wrench space)

Muscle force (muscle force space) → Joint torques (torque space)
The musculo-skeletal system “filters” the propagation of neural commands.
This propagation of neural commands defines feasible inputs and outputs.
Feasible actions are defined by the anatomical routing of tendons

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

Spool, X, Yoshikawa, Brand, Leijnse, Valero-Cuevas, etc.
Feasible actions are defined by the anatomical routing of tendons

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Feasible actions are defined by the anatomical routing of tendons.

Spoor, An, Yoshikawa, Brand, Leijnse, Valero-Cuevas, etc.
Building a feasible torque set for a “complex” limb

Building a feasible torque set for a “complex” limb

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Building a feasible torque set for a “complex” limb

Building a feasible torque set for a “complex” limb
Building a feasible torque set for a “complex” limb

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 $\equiv$ feasible torque and force sets that include the origin

convex sets remain convex under linear mapping

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

All’s well
All’s well

...but

m1
m2
m3

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

At least $N+1$ well-routed muscles
Wait a minute… but $N + 1 > N$
Wait a minute... but $N+1 > N$

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

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

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

(and later we will see how having more muscles allows us to meet more function constraints)
And each tendon contributes in unique ways

flexors produce positive torque
And each tendon contributes in unique ways

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?
Redundancy does not imply robustness

With Jason Kutch

*J Biomech 2011*

Now assistant professor at USC
Dimensionality and structure of the feasible input (solution space) for a given task

Computational Geometry
Vertex Enumeration (dual of Linear programming)
No cost function needed, simply description of feasible inputs and outputs!

Dimensionality and structure of the feasible input (solution space) for a given task

 feasable input space

 feasable output space

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**Computational Geometry**

**Vertex Enumeration (dual of Linear programming)**

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Computational Geometry
Vertex Enumeration (dual of Linear programming)
No cost function needed, simply description of feasible inputs and outputs!

Some muscles are more redundant than others!

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
Some muscles are more redundant than others!
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Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
Some muscles are more redundant than others!

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
Some muscles are more redundant than others!
Some muscles are more redundant than others!
Some muscles are more redundant than others!

This muscle is necessary!!

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
Can we show this for real systems?
Joining the XVI and XXI centuries

Anatomy Lesson of Dr. Tulip
Rembrandt 1632

Valero-Cuevas et al, 2000-present

Turn to age-old physical testing because biomechanical modeling remains a challenge
Record the real input-output mapping

- **Input**
  - Muscle activation
    - (activation space)
  - Muscle force
    - (muscle force space)

- **Output**
  - Endpoint forces and torques
    - (wrench space)

**Muscles** → **Muscle force** → **Joint torques**

**Robotic Arm**

**Extension Spring**

**Safety Shield**

**Fixation Device**

**Dynamometer**

**Block diagram of transformations in a forward limb model**
What is the set of all muscle actions to produce a given force?
A subset of 7-dimensional space!

A. Constrain only radial force

Kutch & Valero-Cuevas, 2011
What is the set of all muscle actions to produce a given force?
A subset of 7-dimensional space!

A. Constrain only radial force

B. Constrain only radial and dorsal force

What is the set of all muscle actions to produce a given force?
A subset of 7-dimensional space!

Kutch & Valero-Cuevas, 2011
What is the set of all muscle actions to produce a given force? A subset of 7-dimensional space!

A. Constrain only radial force

B. Constrain only radial and dorsal force

C. Constrain radial, dorsal, and distal force (produce a well directed force)

Kutch & Valero-Cuevas, 2011
What is the set of all muscle actions to produce a given force?
A subset of 7-dimensional space!

A. Constrain only radial force

B. Constrain only radial and dorsal force

C. Constrain radial, dorsal, and distal force (produce a well directed force)

Kutch & Valero-Cuevas, 2011
Neuromechanical Concept #2

What is the nature and structure of feasible sets?
A first approach: the bounding box
A first approach: the bounding box

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
A first approach: the bounding box

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
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Kutch & Valero-Cuevas, 2011
A first approach: the bounding box
A first approach: the bounding box

Valero-Cuevas et al., 1998
Kutch & Valero-Cuevas, 2011
Chapter 9
Use computational geometry to find the structure of these high-dimensional subspaces.
The Hit-and-Run algorithm can sample such subspaces in up to 40 dimensions!
We can now sample subspaces in up to 40 dimensions to provide a statistical description of their structure.

Submaximal force

Near maximal force
Applied to a 7-muscle finger model producing static force

4D solution space embedded in 7D

Valero-Cuevas et al 1998
Histograms (Bayesian priors) of activation to produce static force of different magnitudes.

- **low force magnitude**
- **maximal force magnitude**

Shows how redundancy is lost!
Big Data approach to motor control: Parallel coordinates visualization with associated cost for each solution.
Summary about muscle redundancy
Summary about muscle redundancy

- Redundancy does not imply robustness
Summary about muscle redundancy

- **Redundancy does not imply robustness**
- Every muscle contributes *uniquely* to function
Summary about muscle redundancy

- Redundancy does not imply robustness
- Every muscle contributes uniquely to function
- More muscles allow more complex tasks
Summary about muscle redundancy

• Redundancy does not imply robustness
• Every muscle contributes uniquely to function
• More muscles allow more complex tasks
• We have barely enough muscles for real-world tasks!
The nature and structure of feasible sets
The nature and structure of feasible sets

- **Co-contraction** is often not an option, and in fact loses meaning
The nature and structure of feasible sets

- **Co-contraction** is often not an option, and in fact loses meaning
- **Agonist-antagonist** language loses meaning
The nature and structure of feasible sets

• **Co-contraction** is often not an option, and in fact loses meaning
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• **Synergist muscles** are not obvious or invariant
The nature and structure of feasible sets

- Co-contraction is often not an option, and in fact loses meaning
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- Synergist muscles are not obvious or invariant
- We do not have to settle for optimization approaches. We can know the entire solution space!
The nature and structure of feasible sets

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• Critical evaluation of **synergies**
The nature and structure of feasible sets

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- Critical evaluation of synergies.
- The statistical structure of the solution space shows the path to probabilistic motor control.
The nature and structure of feasible sets

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The nature and structure of feasible sets

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- Critical evaluation of **synergies**
- The statistical structure of the solution space shows the path to probabilistic motor control
- **Motor control is a Big Data problem**
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
Roadmap to computational exercises

Brian Cohn
This book provides a conceptual and computational framework to study how the nervous system exploits the anatomical properties of limbs to produce mechanical function. The study of the neural control of limbs has historically emphasized the use of optimization to find solutions to the muscle redundancy problem. That is, how does the nervous system select a specific muscle coordination pattern when the many muscle of a limb allow for multiple solutions? I revisit this problem from the emerging perspective of neuromechanics that emphasizes finding and implementing families of feasible solutions, instead of a single and unique optimal solution. Those families of feasible solutions emerge naturally from the interactions among the feasible neural commands, anatomy of the limb, and constraints of the task. Such alternative perspective to the neural control of function is not only biologically plausible, but sheds light on the most central tenets and debates in the fields of neural control, robotics, rehabilitation, and brain-body co-evolutionary adaptations. This perspective developed from courses I taught to engineers and life scientists at Cornell University and the University of Southern California, and is made possible by combining fundamental concepts from mechanics, anatomy, robotics and neuroscience with advances in the field of computational geometry. Fundamentals of Neuromechanics is intended for neuroscientists, roboticists, engineers, physicians, evolutionary biologists, athletes, and physical and occupational therapists seeking to advance their understanding of neuromechanics. Therefore, the tone is decidedly pedagogical, engaging, integrative and practical to make it accessible to people coming from a broad spectrum of disciplines. I attempt to tread the line between making the mathematical exposition accessible to life scientists, and convey the wonder and complexity of neuroscience to engineers and computational scientists. While no one approach can hope to definitively resolve the important questions in these related fields, I hope to provide you with the fundamental background and tools to allow you to contribute to the emerging field of neuromechanics.

http://valerolab.org/fundamentals

Chapters 7, 8 and 9
Define your input-output relation

Motor Cortex

Motorneuron

Muscles

Tendons & joints

Bones

Input

Muscle activation

(muscle activation space)

Muscle force

(muscle force space)

Joint torques

(torque space)

Output

Endpoint forces and torques

(wrench space)
Define your input-output relation

Motor Cortex

Muscle activation (activation space)

Motorneuron

Muscle force (muscle force space)

Tendons & joints

Joint torques (torque space)

Bones

Endpoint forces and torques (wrench space)
Define your input-output relation

Motor Cortex

Input
Muscle activation
(activation space)

Muscles
Muscle force
(muscle force space)

Tendons & joints
Joint torques
(torque space)

Bones

Output
Endpoint forces and torques
(wrench space)

Motorneuron

Extensor

Flexor
Define your input-output relation

Motor Cortex

Motorneuron

Muscle activation

Muscle force

Tendons & joints

Joint torques

Bones

Endpoint forces and torques

Input

Muscles

Tendons & joints

Bones

Output

Muscle activation

Muscle force

Joint torques

Endpoint forces and torques
Find the bounding box of the feasible static force of a 31-muscle 3D cat hindlimb

The Nature and Structure of Feasible Sets

Fig. 9.3 Moment arms of the 7 DOF, 31 muscle cat hindlimb model [2]. Figure adapted with permission from [70]
Implement Vectormap

9.4 Vectormap Description of Feasible Sets

(a) Take the example of a 2D feasible force set, where that polygon is enclosed in a circle. The thin black lines emanating from the origin are the lines of action of each of the 31 muscles. The distance from the origin to the boundary of the feasible force set (i.e., the maximal force in that direction) is assigned a color, blue for small and yellow for large, as shown for the eight rays emanating from the origin. That color-code is vectormapped onto that point on the circle as shown for the posterior, anterior, dorsal and ventral directions, and 4 others in between.

(b) The same can be done for a 3D feasible force set that is a polyhedron enclosed in a sphere (only the cross-section of the sphere is shown).

c) The color on the surface of the sphere now contains all the information of the enclosed feasible force set—but in a more intuitive way that can be compared across directions and 3D feasible sets. Adapted with permission from [70]

This same methodology can be used to represent feasible activations. Take for example the feasible activations associated with the spherical vectormap of the feasible force set shown in Fig.9.4c. For each 3D direction of the feasible force set, that muscle is associated with a particular activation level. These values are found from the optimal, unique coordination patterns that produce maximal force in each of those directions mapped onto the spherical vectormap of the feasible force set. If you collect all such unique values, they are in fact a 3D object, whose vectormap can be shown in 3D. Consider the case of one single muscle, say the vastus lateralis, as shown in the top row of Fig.9.6. The large vector path shows the
Species average

orientation as above
Implement Vectormap

9.4 Vectormap Description of Feasible Sets

Vastus Lateralis

Lower bounds

Upper bounds

Muscle activation

0 0.5 1.0

Ventral

Medial Gastrocnemius

Posterior

Lateral

Soleus

Anterior

α = 50%

α = 60%

α = 70%

α = 80%

α = 90%

α = 100% (f_{max})

Figure adapted with permission from [70]
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