Alessandro 2014

Synergies

"We show that a control architecture based on synergies can greatly reduce the dimensionality of the control problem, while keeping a good performance level.”

“synergies should embed features of both the desired tasks and the system dynamics.“

If you want to use synergies to do complex tasks, break that complex task down into multiple easy tasks that synergies can accomplish. This keeps the synergy count low.

Alessandro 2018

Synergies

“the CNS compromises between restoration of task performance and regulation of joint stresses and strains”

Hypothesis: the body acts to reduce stresses and strains about joints

Task performance explanation of muscle synergy organization is insufficient for explaining everything the CNS is doing

CNS is doing things internally to regulate as well as externally

Instead is increasing activation of a redundant muscle to accomplish tasks (the task specific approach) the body shifted load to another muscle. This indicates it was prioritizing internal forces.

Almeida-Silveira 1999

Muscle Parameters

Suspended rats for 21 days and analyzed how that impacted tendon characteristics

Less use of a tendon lowers its maximal stress

PCSA of the Achilles doesn’t change significantly

An 1984

Muscle Moment Arms

Measuring moment arms in accurately in small joints is difficult because marker placement can affect it dramatically

There are multiple ways of examining muscle moment arms experimentally, including models and X-Ray

Anderson 2001

Optimization

Compares dynamics optimization solution to two static opt solns

There’s little impact in including the FLV properties of muscle when doing optimization

Dynamic opt may still be preferable if 1) kinematic data is unavailable or bad 2) you need to incorporate activations 3) two other cases

Anderson 2001b

Optimization

Used more muscles in dynamic opt than anyone before

Used minimal constraints, only used kinematic data to specify initial and final states

Some deviations from predictions stem from a limited model of the foot

Arm swing could be important to reducing energy during walking

Problems could come from model being “lumped parameter”, all sarcomeres use same parameters

Andrada 2013

Gait switching

Animals switch gait patterns when they have to use more energy, gaits become less symmetric as the slope changes

“While the animals preferred the walk (symmetrical gait) during horizontal locomotion on the pole, they switched to a more asymmetrical fast walk or grounded running (trot without aerial phases) at 30° of substrate inclination.”

Animals walk more nimbly (lower GRFs) on poles or compliant floors

“Surprisingly, maximal joint torques during walking and climbing did not differ significantly.”

Gait switching may be used as an alternative to added torque when the maximum torque capability is reached

Aoi 2013

Synergies

Broke down locomotion control into 4 square pulses for nominal and added one for object avoidance

Analyzed phase offsets between leading and trailing limbs while avoiding obstacles

Berniker 2016

Muscle Parameters

Even if we know the signals sent to muscles, their responses can be unpredictable

This comes from 1) motor noise or 2) variability between the command-output relationship

This paper compares two FES controllers – one that accounts for uncertainty and one that doesn’t

“This representation characterizes a probabilistic relationship between stimulation levels and evoked forces, whereby each stimulation induces a distribution over possible forces.”

It is important to account for errors in your model due to uncertainty and inherent physiological muscle noise

Berniker 2009

Synergies

How you define the task and requirements changes the synergies you get out

Four controllers are presented (3 synergy based and one muscular based) and compared

Basically just “it works and this is how we did it”

Bouisset 1973

Educational

Dives into the FL and FV curves

Relates the integrated EMG signal to muscle force

There is a linear relationship between the integrated EMG and the isometic force

“Fig. 6 Linear relation between integrated EMG and isometric force for human calf muscles.”

“there is a relation between the integrated EMG of the muscle equivalent (Q) and the external force (f) exerted … it has been shown to be a linear relationship [BAYER and FLECHTENMACHER, 1950; LIPPOLD, 1952; SCHERRER and BOURGUIGNON, 1959; SoLoMON *et al.,* 1965, etc”

Good for reading up on general muscle characteristics and how different curves relate to EMG

Brown 1996

Muscle parameters

Muscle model of the cat soleus

Compares different models for curves and determines the ones that best fit their data

Nice because it acts as a sort of model review, plenty of viable equations

Buchanan 1986

Optimization/ST Curve

EMGs of elbow muscles increased linearly with elbow torque

Hypothesizes that synergies are encoded in upstream neurons in the form of torque (neurons specify torque)

Assumes muscle moment arms are constant

Buchanan 2004

Educational

Clarifies that this work ( and the work I’ve been doing) is a “forward dynamics approach”

This can be a problem because the optimization methods are not biologically verified, which is overlooking the exact role of the central nervous system

Also, determining lines of action and moment arms is hard

Inverse dynamics involves directly measuring the forces or torques

Wealth of modeling information from muscle curves to EMG modeling

Buchanan 1996

Optimization

Analyzes cost functions for muscle force optimization

“*no particular cost function was found to adequately represent actual muscle activity at the elbow”*

“It is obvious from muscle tuning curve results that optimization predictions depend heavily on the number of degrees of freedom which are actively balanced”

“a detailed description of a specific task could not necessarily be coupled with the optimization of an identifiable objective.”

Interesting because this paper does what I was planning, comparing different optimization functions, specifically those from Crowninshield and Pedotti

Buschmann 2015

Review

Functional approach vs Morphological graphic on Fig. 9

Charles 2016

Muscle moment arms

Analyzes the moment arm profiles of a mouse

Provides xyz-coordinates for muscle insertions

Cleland 1867

Historical

Analysis of biarticular muscles

Not much of data substance here but a lot of anecdotal observations as they relate to horse anatomy

Chiel 1997

“Despite successes in [analyzing nerve cells], … adaptive behavior can best be understood within the context of the biomechanics of the body, the structure of an organisms environment, and the continuous feedback between the nervous system, the body and the environment”

Motor neuronal output is heavily post-processed by the muscle, tendon, and mechanical advantage of a muscle (an example of the body acting as a filtering device between the environment and neural firing)

You can’t just “peel away” the body and expect natural responses from the nervous system

Nervous system and body are further intertwined because there’s evidence that, as animals evolve, their body structure AND nervous system evolve in concert

Nerves activate in a way that maximizes the effectiveness of the muscles that they innervate

If you restrict a rat’s leg for two weeks after birth, it’ll still be able to walk afterward but the timing of EMG signals will be sub-optimal, suggesting that neural entrainment is dependent on peripheral codevelopment

“In the absence of feedback from an animal’s own movements, the nervous system may not generate meaningful activity patterns for behavior.”

A predator and prey’s movements depend on what the other animal is doing, same thing if we consider an animal-environment interaction

“Instead of asking ‘What is the neural basis of adaptive behavior?’, one should ask ‘What are the contributions of all components of the coupled system and their interactions to adaptive behavior?’”

Cofer 2010

Educational

Animatlab presentation

Corcos 1992

Optimizations/ST Curve

Electromechanical delay in muscle force generation is caused by two things 1) transmission speed ( usually around 10ms) and the time to generate detectable changes in force.

The second part usually takes longer and has to do with the “forces produced by cross-bridge cycling or the movement that the forces produce”

This is entirely an experimental problem and not something that occurs in the body

The better analytical tool we use, the more we can cut this down

Crowninshield 1981

Optimization

This method uses the nonlinear relationship between muscle contraction force and endurance to sort muscle forces from joint torques

Interesting presentation of optimization solution spaces

“The prediction of few simultaneously

active muscles resulted from the requirement,

inherent with linear optimization, that the

solution resides at a solution space corner.”

Useful partial review of other optimization papers (Seirig and Arvikar, Hardt, Weber bros, Pedotti

Just because an optimization function yields predicted EMG’s that have good agreement with data doesn’t mean that’s how the body does it

You make a stronger argument if the force predictions generally correlate with muscle size and when the opt function has a physiological analog/basis

D’Avella 2005

Synergies

Broke down three tasks from the frog (jumping, swimming, walking) into a synergy set

Achieved 70% VAF at just 5 synergies for all tasks

Asserts the task-specific-ness of synergy manifestation

D’Avella 2003

Synergies

Developed a new algorithm to identify a set of time-varying muscle synergies

Asserts that because they found synergies, the CNS uses this to simplify its job

Ekeberg 2005

Neural Control

3D sim of that cat hindlimb

Used a combination of Python, C, and OpenGL for simulation

Studied the impact of two sensory mechanisms on the stance-swing transition: force loading at the ankle and hip extension position

Basically found that you need to have the ankle become unloaded and hip extended in order to trigger swing

Unloading of thie ankle is more important because including it will eventually lead to an alternate stepping gait

The hip extension rule would lead to “progressive shifts in coordination and often to falling or collapse of the hindquarters”

Eng 2009

Education

Similar to Johnson 2011 with many muscle parameters

29 muscles six paired hindlimbs were studied

One leg used for fiber-type distribution and the other for architectural measurements

Classifies muscles based on their “action about each joint”

Muscles can be a part of two muscle groups

Compares stats (PCSA, fiber length, mass) between functional groups

Breaks down I, IIA, IIX, IIB fibers in each functional group

Presents some interesting scaling relationship equations for fiber length and PCSA wrt mass

Ettema 1989

Muscle Parameters

Studied EDL in 11 male rats

Aponeurosis = pure muscle, without tendon or tendon insertion

Provides relationships between force and tendon length

Muscles operate at intentionally longer lengths in order to accommodate the disparate shortening velocities of the aponeurosis and muscle-tendon complex

Fischer 2002

Scapula or hip joint are doing the majority of displacement in “zigzag” pattern limb

Contrasts kinematic parameters from symmetric or in-phase gaits

Discusses the impact of pelvis movements during different gaits

Great source for disparity between forelimb and hindlimb kinematics

Gratsch 2019

Neural Control/Neural hierarchy

Reticulospinal cells (RS) in the brain interface with CPGS and “act as command cells for locomotion”

Above RS cells are MLR and DLR cells

Digs a bit into deep brain stimulation by showing that stimulating the MLR (high order lcoomotory cell in the brain) you can induce stable locomotion

Good paper for understanding the possible hierarchy of the nervous system

Greene 1953

Educational

Primer on the anatomy of the rat

Hardt 1978

Optimization

Uses a static optimization method for “minimal force” and “minimal muscle energy”

Remarks that the optimization criteria must be physiologically motivated

Herzog 1991

Optimization

Measured muscle forces from cat soleus, gastroc, and plantaris

Great discussion of the physiological representations (esp shortcomings) of the 5 models

Did not factor in gastroc and plantaris biarticularity when prediction joint torques

Uses 5 different optimization criteria and compares them to experiemental data

Opt criteria:

1. Dul’s minimum fatigue,
2. Crowninshield F/PCSA,
3. Pedotti F^2,
4. Pedotti (F/Fmax)^2,
5. Seireg/Crowninshield F/Fmax

“Models 2 and 4 consistently overestimated the contributions of large muscles compares to those of small muscles” (counting out the impact of the little guys)

Reasserts that nonlinear models are the only way to optimize effectively

Hof 2001

Muscle moment arms

Monoarticular muscles produce forces along the length of a bone segments

This is mostly true when the leg is straight, appears to be less hard and fast rule as the leg is more bent

Biarticular muscles produce more transverse forces

Hoy 1990

Estimating muscle parameters based on LT curves

Developing a muscle force model based on tendon stress and pennation angle

Big on tendon slack length

Tendon stretch is insignificant for calculating actuator force peaks

Many graphs of muscle moments with respect to joint angle

They lump muscles into extensor/flexor for each joint

Do not isolate specific muscles

Hunt 2015

Neurons in our model are” leaky conductance-based models”

Breaks down the tension and HH equations

Describes the joint torque development process

Uses -60mV resting voltage

Missing data to refine the Ib and Ia feedback pathways

Hunt 2014

This is the paper that goes into coordination

This relates the output of the ConnectData routines in the “Main Ani and Sim” folder from Alex

Tests both intra- and inter-leg coordination

Hunt 2017

Applying the subnetwork approach to puppy and analyzing the kinematics

Jarc 2013

Applying FES to a rat, implanting electrodes to stimulate up to 11 muscles

Many stimulus (mA) force curves for different muscles presented

All sigmoids with variable stiffness

Better than a pure computer model bc it avoids “simplifying assumptions”

“the simultaneous activation of multiple muscles combines linearly”

Placed electrodes near motor points in muscles, rather than on nerves themselves

Johnson 2011

Muscle parameters/Optimization

Discussion the formulation of muscle parameter space

Great map of the hindlimb muscle innervation tree

Suggestions about grouping muscles

Carries out static optimization (a(t)^4)

Analyzes force production envelopes at different postural configurations

Constraining muscles to activate based on innervation groups reduces the space of forces producible in the hindlimb

More degrees of activation freedom leads to a higher force space envelope

Johnson 2008

Muscle attachment points/Muscle moment arms

Provides xyz-coordinates of every muscle attachment point

Kaufman 1991

Optimization

Introduces a new muscle model of “normalized active length-tension relationship”.

Optimization methods which minimize forces ignore fatigue effects

Mostly just discussing previous optimization methods and stating that this new muscle model could be a better way of representing the LT eqn

Kurtzer 2006

Monoarticular muscles will change their activity even when torque is applied to a joint they do not span

Goes big into differences between biarticular and monoarticular muscles

Monoarticular muscles are most sensitive to induced torque in their preferred direction (shoulder extensors are maximally sensitive to shoulder extension)

Goes against the grain of synergies by saying it was able to achieve similar results without any apriori grouping

Kutch 2011

Muscle synergies

Just because there is muscle redundancy (many muscles to choose from for the CNS), limbs are not immune to muscle loss

Goes against muscle synergy argument by representing the importance of individual muscle contributions over the group

Muscle actions are the result of task demands, not pre-ordained synergies

Lakatos 2016

Robotics

Discusses the formulation of a bipedal robot using equations of motion and vibration analysis

Exploits velocity oscillations to induce walking

Essentially making a mechanical CPG

Lee 2001

Educational

Process for the NNMF

I believe you could just optimize for min(sum(Aij-Bij)^2 in Eqn 2

Lee 2008

Estimating moment arms from 5 finger muscle tendons

Shows differences of including passive joint moments

Joint moments are highly dependent on posture/task since muscle moment arms are affected

Lippold 1952

There is a linear relationship between integrated EMG measurement and tension

Lloyd 2003

Muscle modeling

EMG muscle model

Much stronger experimental agreement than past EMG model

Take time to rationalize why this isn’t simply a curve fitting technique

Making the case that a model doesn’t necessarily have to be physiologically correct to provide an accurate prediction

Use a nonlinear least squares approximation to derive model parameters

Markin 2016

Educational

Modeling the neural control system

Some great muscle modeling equations and techniques in Chapter 6

McCrea 2008

Neural Modeling

Works well as a review for multi-level CPG-design

Talks about the combination of the MLCPG with the unit-burst generator

First proposing the unit pattern formation configuration (what I believe Alex used)

McKay 2012

Synergies

Comparing force optimization prediction to synergy predictions

Found that using synergies “significantly decreased the search time the optimization algorithm required to identify a motor solution”

Suggest that synergies are a “translation” from task-level goals to muscle activation patterns, functioning as a kind of “lookup table”

Morrison 1970

Describing forces generated in a human knee

Describes the movement of the knee joint center during joint motion

Muir 1999

GRFs for hemi-parkinson rats

Has 3D GRFs

GRFs spike when diagonal legs strike (twice per stride)

Forelimbs seems to be more affected by the lesions, hindlimbs “pick up the slack” in terms for generating forces post-lesion

Could be because the forelimbs “perform a more complicated task during locomotion than the hindlimb and is therefor more affects by any lesion”

Murphy 1974

Muscle parameters

All about the cat soleus

Includes a force-velocity diagram from the cat soleus

Murray 1994

Educational

Rigid body transformation, the information behind the manipulator Jacobian for a multi-arm system

Just an all-around great MechE book

Nicolopoulos-Stournaras 1983

Biological neural mapping/Synergies

Physical stained images of the motor neuron columns in the rat spinal cord

Could be useful for synergy groupings

Pearlman 2004

Thumb tip forces do not scale linearly with thumb muscle tensions

Tests thumb muscles doing two different tasks

Pedotti 1978

Optimization

Minimizes four different cost functions and describes their physical meanings

Decides that sum(F/Fmax)^2 is the most effective function because it incurs the highest penalty on F/Fmax ratios

Penrod 1974

Optimization

Optimizing force production in four muscles of human wrist

Minimizing sum(F)

Perrault 2008

Synergies

Refutes the synergy hypothesis by showing that synergistically different groups activate the same for two different tasks

Makes the case for reflexes modulating limb stability, especially in compliant environments

Further makes the case the muscular response is task dependent

Prilutsky 2002

Optimization

Considers four cost functions all related to minimizing fatigue

Says that some cost functions are better for different test subjects – one was better for cats but another was better for humans

They find that the best cost function is the minimal fatigue function sum(F/PCSA)^3

Ranganathan 2016

Refutes the neural control of synergies

This analyzes synergies over time to see if they become further entrenched during a learning process

Synergy composition changes (weights of muscles are different) under different demands

These weighting values change under short timescales, implying that the nervous system is changing their activations individually on the fly, rather than employing a global synergy activation

Rode 2009

Muscle Parameters/Modeling

Compares two Hill models of muscle, one with the series elastic element (SEC) in parallel with the contractile element (CC) and the one that Animatlab uses

Finds that the CC model works best

Sacks 1982

Muscle Parameters

Examining muscle fiber length in cat muscles

Sandercock 2018

VM and VL muscles produce similar forces in knee extension but opposing forces on the patella

Must consider many different actions of a muscle before discounting its redundancy

For example, you have an infinite solution set when considering VM/VL for GRF generation but reduce the problem space considerably when you factor in the necessity to balance patella forces

Savelberg 2003

Synergies and Muscle adaptation

Compares leg muscles between runners and cyclists

Shows that muscles can specialize to adapt to the task of the person (muscle have optimal force generating capabilities in a bent configuration of a biker, for instance)

Schipplein 1991

Antagonistic muscle need to be cocontracted to maintain joint stability

Analyzing passive and active components in the knee to check for stability

Seireg 1973

Optimization

Compares four different optimization methods

Sum(F), sum(f\*|delL|), minimizing vertical reactions in each joint, minimizing the moments carried by the muscle ligaments

The ideal solution seems to be U = sum(F) + 4\*the ligament moments

Sharbafi 2016

Robotics

Robot using biarticular muscles

Spector 1980

Muscle Properties

Compares muscle properties of a cat soleus and MG

Discusses influence of muscle architecture on output curves

Steele 2015

Synergies

Studies a large population (633, 549 CP, 84 NCP)

Surface EMG’s to sort muscles into synergies

Comparing CP individuals to individuals without CP

The number of synergies in CP individuals is lower than those who are unimpaired

Brain injuries seem to reduce the functional control space available for the CNS

Synergy analysis may be useful in treatment planning for stroke survivors, stroke survivors with synergies more similar to unimpaired individuals have greater physical therapy improvements

Steele 2015

Synergies

Synergy algorithms do a poor job of predicting muscle forces when they don’t factor in environmental/task specific restraints

Describes the process of decomposing a synergy into muscle activations

Matrix factorization algorithms expect a reasonable amount of difference between synergy profiles

When you introduce task restrictions, the synergy space narrows and synergies become more similar, something that matrix factorization algorithms struggle with

Including EMG variability improves matrix factorization results (don’t average EMG signals)

Cites some articles supporting the existence of synergies in the biology (Kargo and

Giszter 2000; Overduin et al. 2012).

Szczecinski 2014

Neural design

Model of a cockroach turning

Implementation of biological findings into simulation

Shows that higher stimulation of a turning neuron can affect turning radius

Analyzes leg kinematics

Szczecinski 2017

Neural design

Describes the functional subnetwork approach to neural design

Basic principles for the algebraic circuits

Szczecinski 2017b

Neural control/Robotics

Controlling a system of servos with a SNS design

Contrl of servos with an oscillating CPG

Description of the formulation of the delta factor – the parameters responsible for oscillation speed

Szczecinski 2014b

Neural control/Robotics

Control of MantisBot with SNS

Perturbation response and joint control

Taborri 2018

Synergies/Educational/Review

Interesting articulation of the process of a scientific literature review

Great resource for citations of synergies in robotics

Taborri 2018

Synergies

Statistical analysis of muscle activation as a results of synergy analysis for 5 locomotion actions

Trying to find out is synergy decomposition remains “the same” if you do the decomposition over time for the same subject and same acitivty

Stress the importance of the electrode placement and inclusion of EMG variability moreso than the algorithm choice

Focus on the muscle synergy vectors (W) or temporal activation patterns (c) rather than the number of synergies

Found that synergies were repeatable across subjects and consistent within subjects over time

Thelen 2003

Muscle Parameters

Analyzes the effect of age on muscle mechanics

Includes some great muscle modeling equations for the Fpe, Ft, differential activation dynamics

You can’t simply alter the maximum isometric forces to account for aging muscle, you must actually change the internal parameters of the model itself

Thota 2005

Neural modeling

2D rat limb measurements

Some 3D measurements as well

Includes EMG measurements compared to joint angle trajectories

Ting 2012

Review/ Muscle Synergies

Describes equations for muscle activation and for synergy temporal activation patterns

Discusses the impact of strokes on muscle synergy recruitment

Ting 2005

Synergies

Decomposes four synergies to control cat posture

Reaffirms supremacy of NNMF as the matrix decomposition method

Torres-Oviedo 2007

Synergies

Compares synergy decomposition for variety of subjects and over time

Reaffirms the factorization of synergies being task specific

Shows that different synergy patterns can be used to achieve the same goals

Is it possible, then, that task specificity narrows that solution space?

Tresch 2009

Review/Synergies

Great resource for studies for an and against synergies

Tresch 2006

Muscle Synergies/Math

Compares different matrix factorization methods and articulates the algorithms for implementing them

The consistency of certain algorithms reassures that the resulting data has less to do with the algorithm itself and more to do with the concrete things in the data

Tresch 1999

Synergies

Identification and classification of synergy presence in a frog hindlimb

Valero-Cuevas 2015

Muscle Redundancy

Presents two examples of applying computational methods to neuromechanical models

Force plots are difficult to interpret, 3D spheres?

Valero-Cuevas 2009

Synergies

Argues against synergies

Says that the CNS is simply trying to reduce the amount of energy expended for each action

Demonstrates individual muscle action for control of a task, instead of synergy

Shows that the EMG signals of task-relevant muscles have reduced variability when engaged and that other muscles have more variance

CNS is simply “paying attention” to certain muscles when it needs to do something

Visser 1990

Muscle moment arms

Shows muscle moment arm profiles over range of joint angles for a human leg

Wei 2018

Optimization/3D modeling/Sensitivity Analysis

Uses a 3D rat hindlimb model

Compares measured and predicted muscle forces in that 3D model

They use an iterative optimization method to bring muscle attachment points in line with pre-defined generalized coordinates

Their predicted muscle force vectors vary as a result of bony landmark variance – they do a sensitivity analysis of the bony landmarks, shifting them, and see how it changes the force vector

Really interesting method for sensitivity analysis

Wenger 2016

Biological

Stimulating muscle synergy centers in the spinal cord improve motor control after SCI

Oscillating neural stimulation at the spinal cord in synergy “region” offered the best restoration of locomotion compared to drugs replacement therapy and direct, constant electrical stimulation

Primary delivery is that spinal cord “epidural electrical stimulation” should be applied in a more effective way than static, constant stimulation

If we sort those spinal regions into “synergy” center, then we can oscillate between them

Williams 2008

Moment Arms

Analyzing muscle moment arms in racing dogs

Shows no correlation between muscle fascicle lengths and its maximum moment arm

Witte 2002

Shows GRFs over many trials of a guinea pig walking

Shows percentage of joint torques caused by GRFs over stance

Shows torques at the joints over stance

Yeo 2013

Muscle modeling

Compares three muscle models and considers their predicted FLV results to experimental data

Yeo 2011

Muscle moment arms

Very similar to Wei 2018, compares predicted and measured muscle force vectors in the rat hindlimb

Uses Johnson and Eng data

Zajac 1989

Educational

Basically wrote the book on muscle modeling