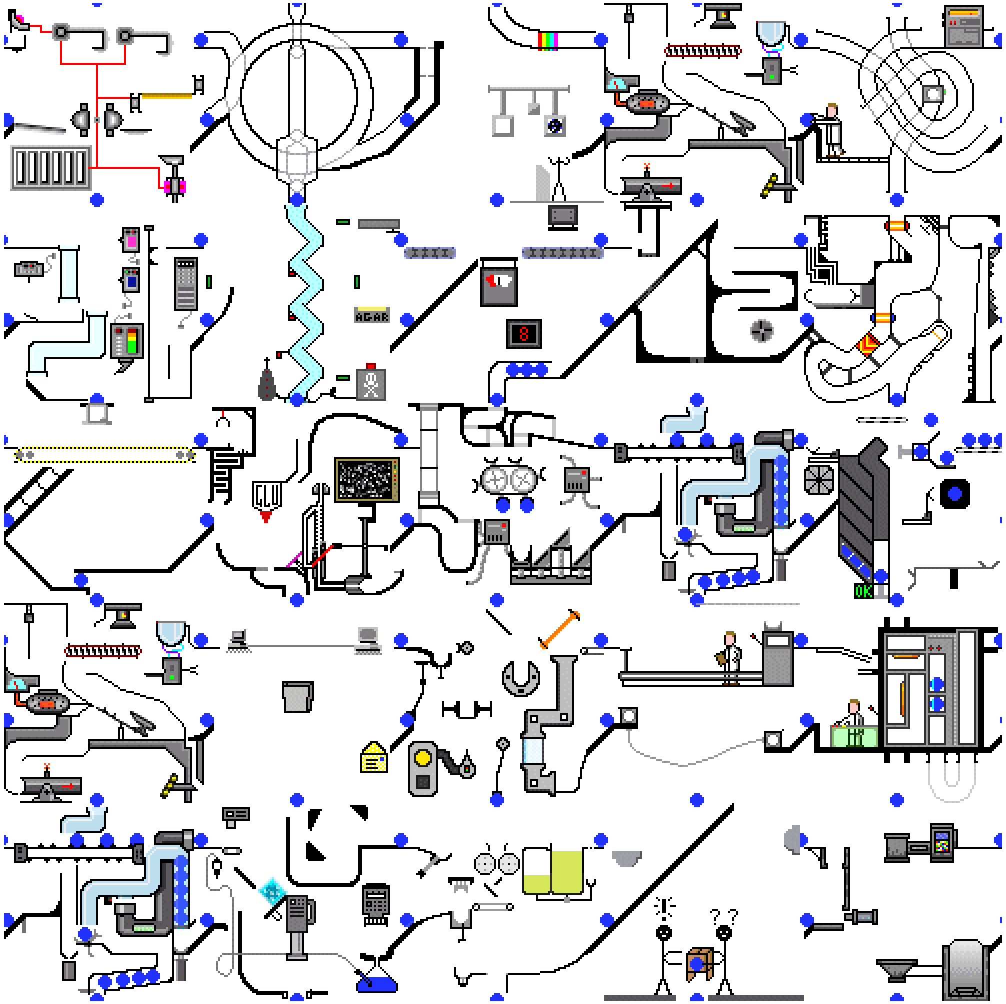


Systems-level Modeling

Lecture 3

BME 599: Modeling & Simulation of Movement

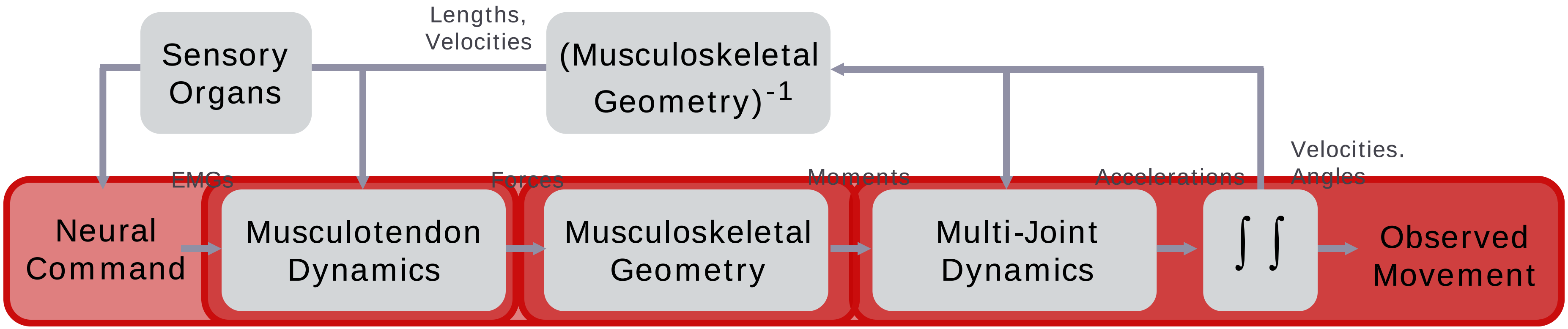
Question of the Day

Why is understanding muscle coordination of movement complex?

Outline for Today

- Question of the day
- Systems-level modeling overview
- Zajac, 1993
- Similarities and differences in Buchanan et al., 2004 and Erdemir et al., 2007
- Help with simulation of jumping
- Answer your questions!

Systems-level Modeling Overview



- Lab 1: dynamic simulation of jumping
- Lab 2: modeling musculoskeletal geometry
- Lab 3: torque-driven simulation of swing
- Lab 4: dynamic modeling and simulation of muscle-tendon
- Lab 5: muscle-actuated simulation of swing

Outline for Today

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Journal Reviews

- The purpose of reviewing these papers is to supplement and broaden the lab experience
- Student reviews of papers make the course more interesting, fun, and instructive

Zajac, 1993

Muscle Coordination of Movement

Why do the basic principles of movement coordination remain unclear, despite years of detailed recording and analysis of kinesiological data?

- Need to understand many movements, develop biomechanical models, and record relevant experimental data
- Need for forward dynamic simulation to compliment experiments

Third and fourth paragraphs of Introduction

J. Biomechanics Vol. 26, Suppl.1, pp. 109-124, 1993.
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MUSCLE COORDINATION OF MOVEMENT: A PERSPECTIVE

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Abstract—Multijoint movement requires the coordination of many muscles. Because multijoint movement is complex, kinesiological data must be analyzed and interpreted in the context of forward dynamical models rich enough to study coordination; otherwise, principles will remain elusive. The complexity arises because a muscle acts to accelerate all joints and segments, even joints it does not span and segments to which it does not attach. A biarticular muscle can even act to accelerate one of the joints it spans opposite to its anatomical classification. For example, gastrocnemius may act to accelerate the knee into extension during upright standing. One powerful forward dynamical modeling method to study muscle coordination is optimal control theory because simulations of movement can be produced. These simulations can either attempt to replicate experimental data, without hypothesizing the purpose of the motor task, or otherwise generate muscle and movement trajectories that best accomplish the hypothesized task. Application of the theory to the study of maximum-height jumping has provided insight into the biomechanical principles of jumping, such as: (i) jump height is more sensitive to muscle strength than to muscle speed, and insensitive to musculotendon compliance; (ii) uniarticular muscles generate the propulsive energy and biarticular muscles fine-tune the coordination; and (iii) countermovement is often desirable, even in squat jumps, because it seems both to prolong the duration of upwards propulsion, and to give muscles time to develop force so the body can move upwards initially with high acceleration. The effort necessary to develop forward dynamical models has been so high, however, that model-generated data of jumping or any other task are meager. An interactive computer workstation environment is proposed whereby users can develop neuromusculoskeletal control models, generate simulations of motor tasks, and display both kinesiological and modeling data more easily (e.g., animations). By studying a variety of motor tasks well, each within a theoretical framework, hopefully muscle coordination principles will soon emerge.

INTRODUCTION

Human movement, performed with its usual gracefulness, demands the coordination of many muscles. Understanding how and why the body coordinates muscles intrigues professionals spanning diverse disciplines, such as sports, the performing arts, engineering, and medicine. For example, as biomechanicians we may attempt to elucidate how the body segments and muscles interact mechanically to execute motor tasks. As motor control neuroscientists we may focus on elucidating the properties of the central nervous system controller. As rehabilitation scientists, we may study human pathological movement to develop musculoskeletal or neurological therapies.

One would think, then, that by synthesizing the collective knowledge from all the disciplines we could postulate (and perhaps agree on) some principles subserving muscle control of movement. I submit, however, that we are far from achieving this goal. Why do muscle coordination properties remain elusive?

I believe the crux of the problem is that we rarely understand (and agree on) how muscles coordinate any one movement, much less a repertoire of movements. And many movements need to be understood before we can hope to postulate broadly applicable muscle coordination principles. To attain an understanding of muscle coordination of many movements, do we need to just collect more biomechanical and kinesiological data? Though observing how subjects execute a variety of movements is certainly essential to the formulation of hypotheses, it is not sufficient.

A biomechanical model of each movement being studied is also essential. In addition, the models must be sufficiently complex to elucidate muscle coordination principles. Progress will be sustained in movement science by our ability to both develop biomechanical models and record relevant experimental data. For example, often *inverse* dynamical models are hypothesized in order that the net muscle moments about the joints can be estimated from the experimental data. However, *forward* dynamical models offer more potential to studies of multimuscle control of movement (see below, "Integrating Experiments and Models to Study Muscle Coordination"). In movement science, I submit that our ability to construct and use *forward* dynamical models complex enough to study muscle coordination has lagged behind our ability to collect biomechanical and kinesiological data.

In this paper, I will first review why forward dynamical models are so necessary to understand how muscles coordinate a multijoint motor task. Second, forward and inverse dynamics approaches to integrating experiments and models to study muscle coordination will be reviewed. Third, vertical jumping will be used as a case study to show how forward dynamics

*Address for correspondence.

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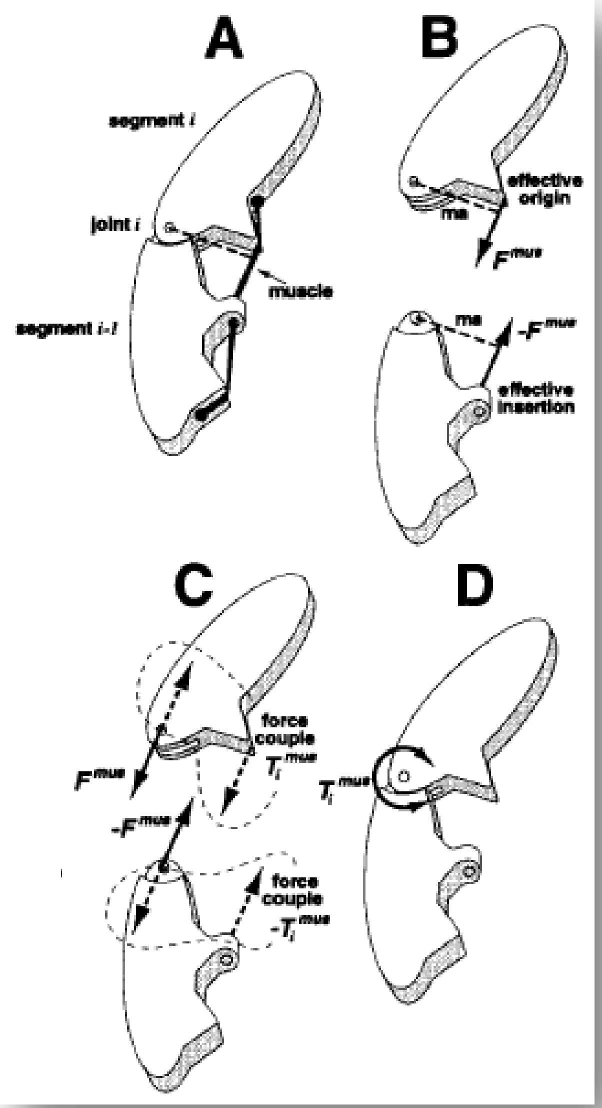
Zajac, 1993

Joint Torque from Muscle

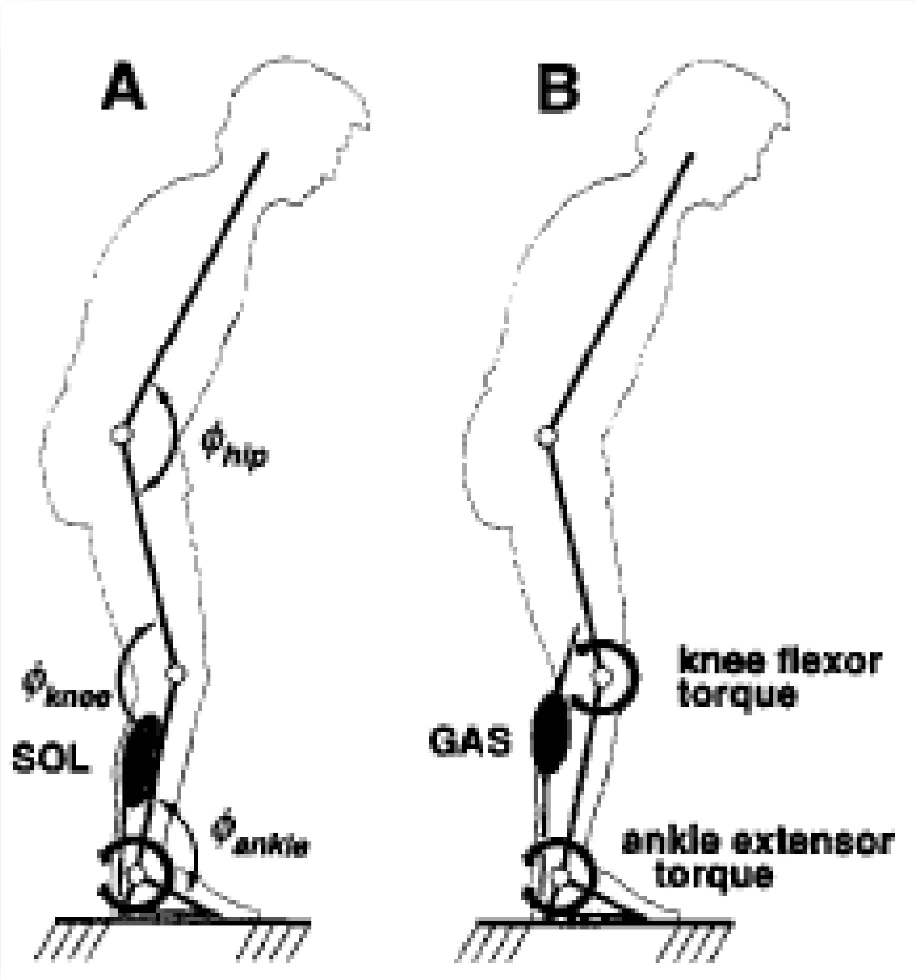
- Muscle generates force
- Uniarticular muscle (A) will have two forces (B)
- In combination with joint reaction forces, there are two couples generating torques (C)
- For a frictionless joint (D), only the two torques (not forces) contribute to accelerations



Zajac, 1993

Anatomical Classification and Function

- Classified by direction of joint torque
- Uniarticular: easy
  - Soleus is always an ankle extensor
- Biarticular: difficult
  - Gastrocnemius is uniarticular if one joint is constrained (brace)
  - If unrestrained, it may do non-intuitive things



Why Forward Dynamical Models Are Necessary to Study Coordination

Zajac, 1993

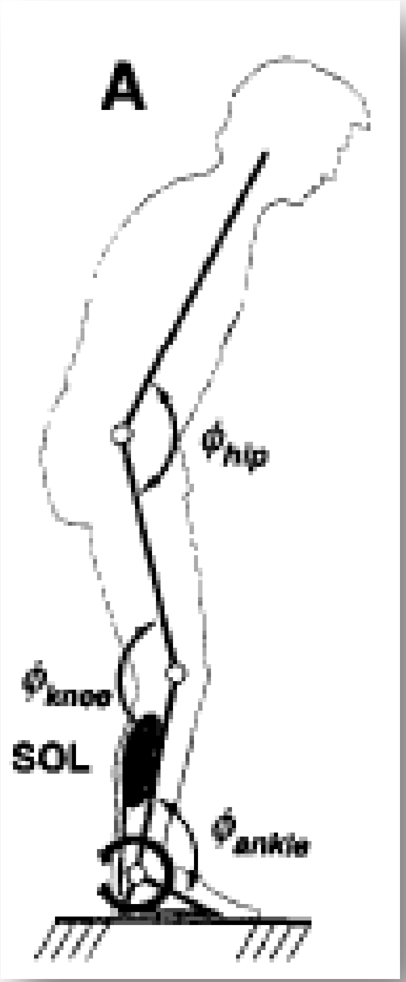
Accelerating Joints Not Spanned

- In A, soleus accelerates knee 2x as much as the ankle
  Why?
  - Inertia forces transmitted via joint reaction forces
  - Equations of motion

    $$M(\phi)\ddot{\phi} = T^{mus} + V(\phi,\dot{\phi}) + G(\phi) \qquad (1)$$

    - Mass matrix (M), joint torques from muscles (T^{mus}), centripetal and coriolis (V), and gravity (G)
  - Net angular accelerations

    $$\ddot{\phi} = M^{-1}(\phi)T^{mus} + M^{-1}(\phi)V(\phi,\dot{\phi}) + M^{-1}(\phi)G(\phi) \quad (2)$$

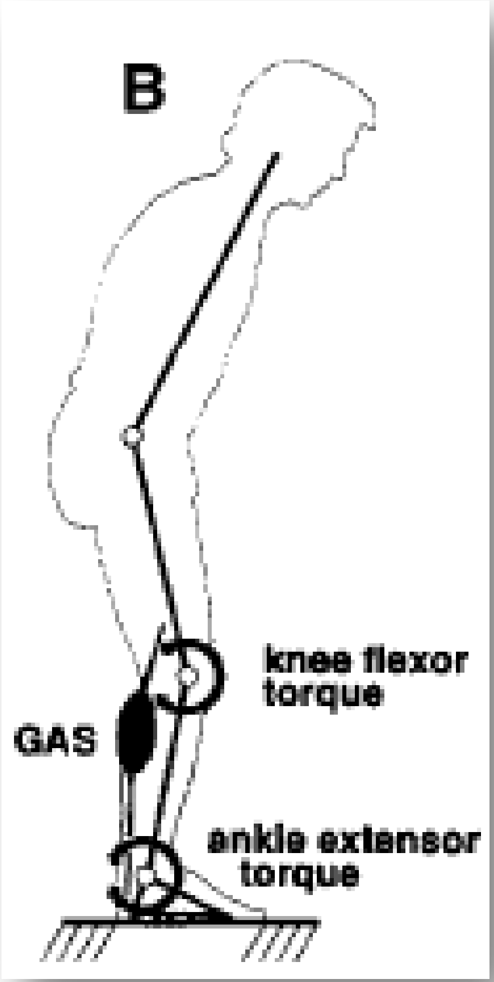


Zajac, 1993

Biarticular Muscles Can Accelerate Joints Opposite to Its Joint Torque

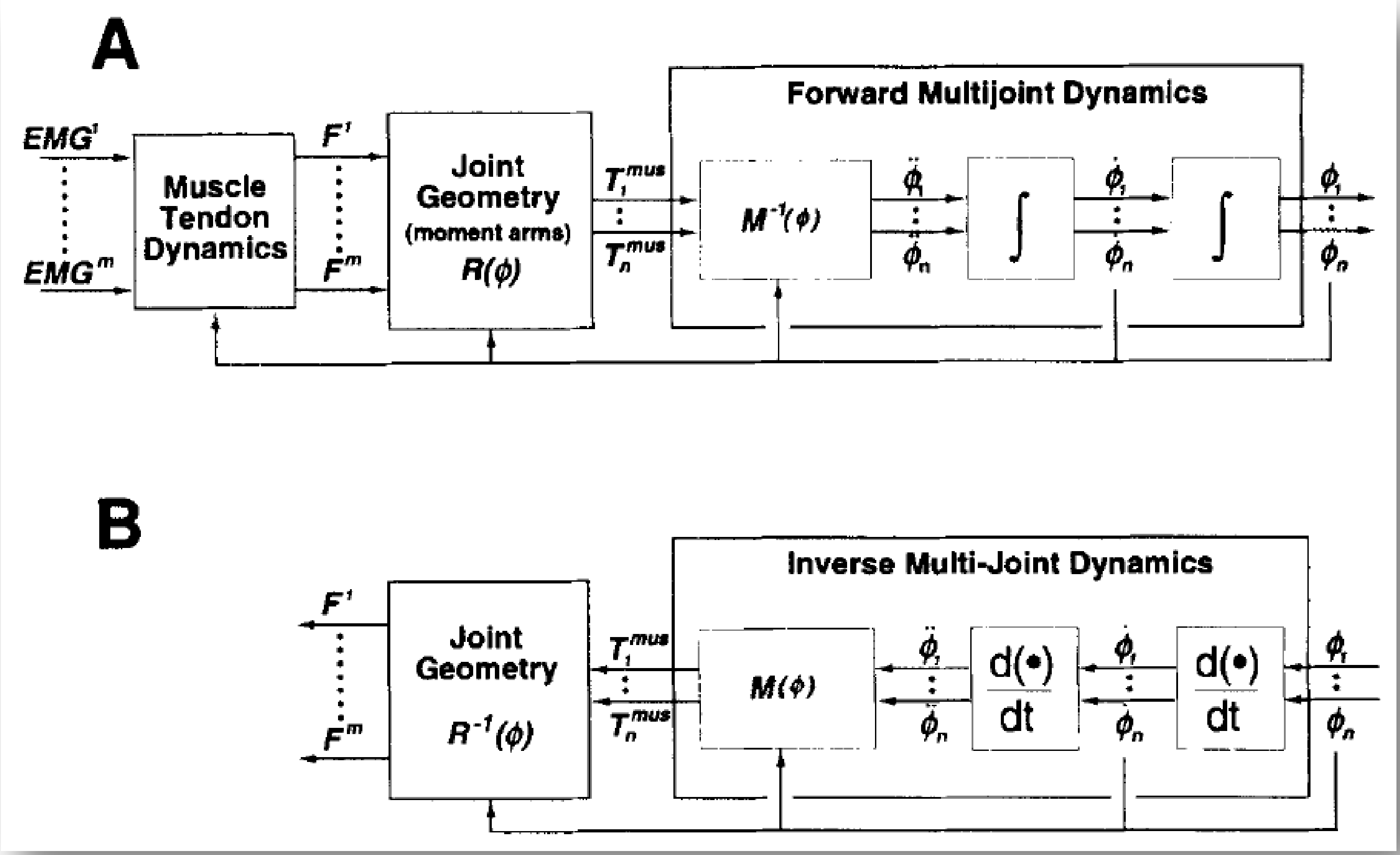
$$\begin{bmatrix} \ddot{\phi}_{ankle} \\ \ddot{\phi}_{knee} \\ \ddot{\phi}_{hip} \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdot \\ \alpha_{21} & \alpha_{22} & \cdot \\ \alpha_{31} & \alpha_{32} & \cdot \end{bmatrix} \begin{bmatrix} T^{GAS}_{ankle} \\ T^{GAS}_{knee} \\ 0 \end{bmatrix} \qquad (4)$$

- Due to inertial (or dynamic) coupling seen in the mass matrix
- In B, gastrocnemius generates torques and accelerations
  - Knee flexor and ankle extensor torques
  - Three acceleration conditions
    - Knee flexion and ankle extension
    - Knee flexion and ankle flexion
    - Knee extension and ankle extension



Zajac, 1993

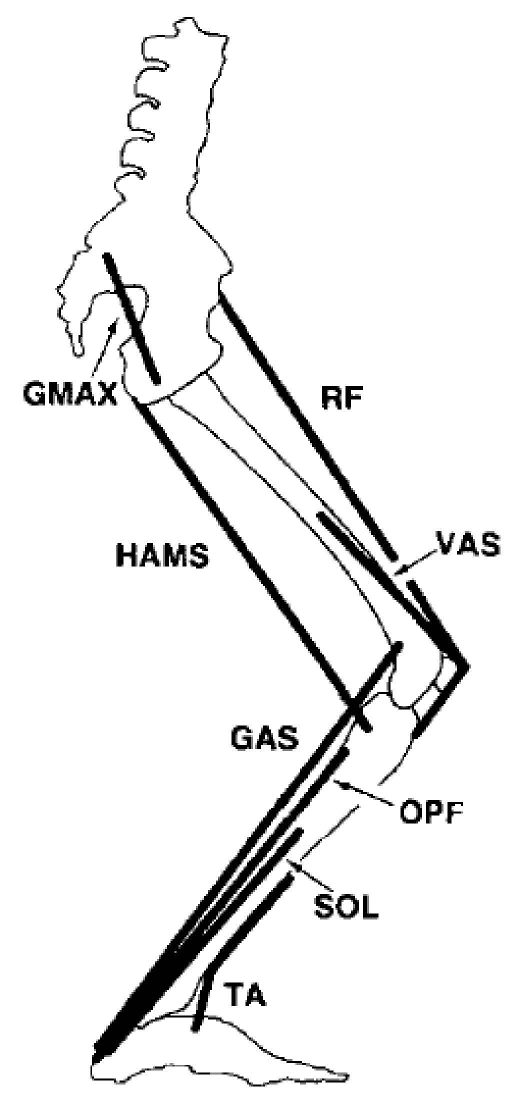
Forward (A) vs. Inverse (B) Dynamics



Zajac, 1993

Analysis of Jumping

- Should lower limb muscles by fully excited? If so, which ones and when?
  - Yes for uniarticular extensors during propulsion
  - No for uniarticular flexors
  - Maybe (on-off) for biarticular muscles

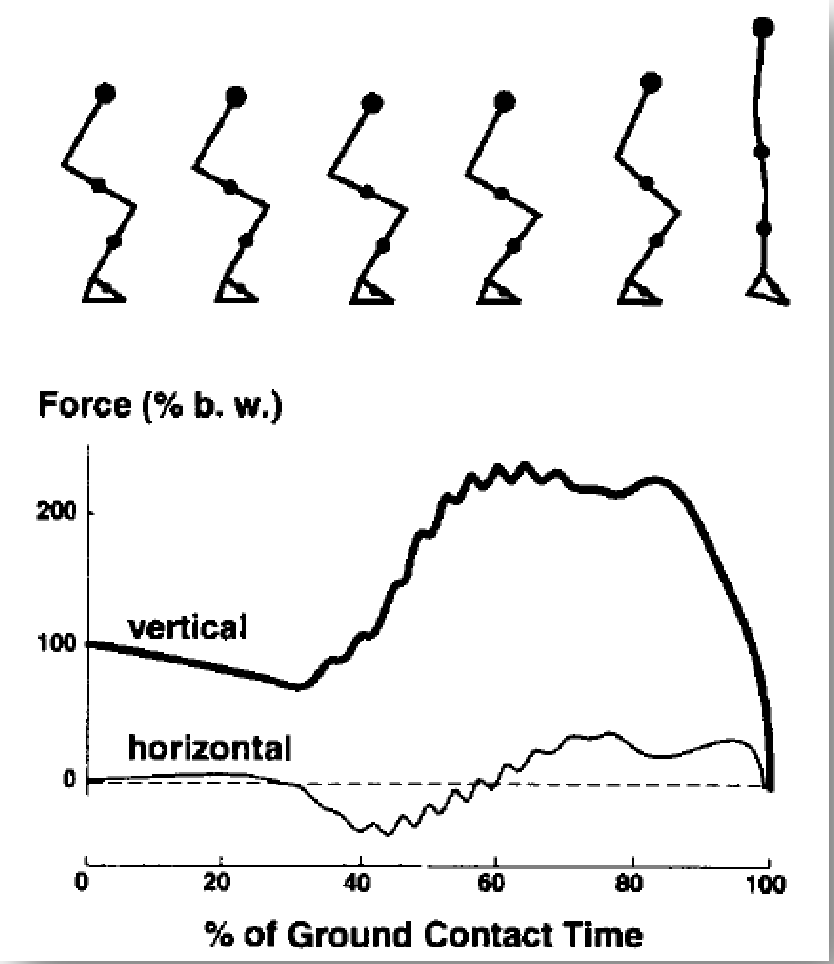


Muscle Coordination in Vertical Jumping: A Case Study

Zajac, 1993

Analysis of Jumping

- Is jumping height more sensitive to muscle strength or to speed?
  - Strength (120%)
  - Speed (60%)

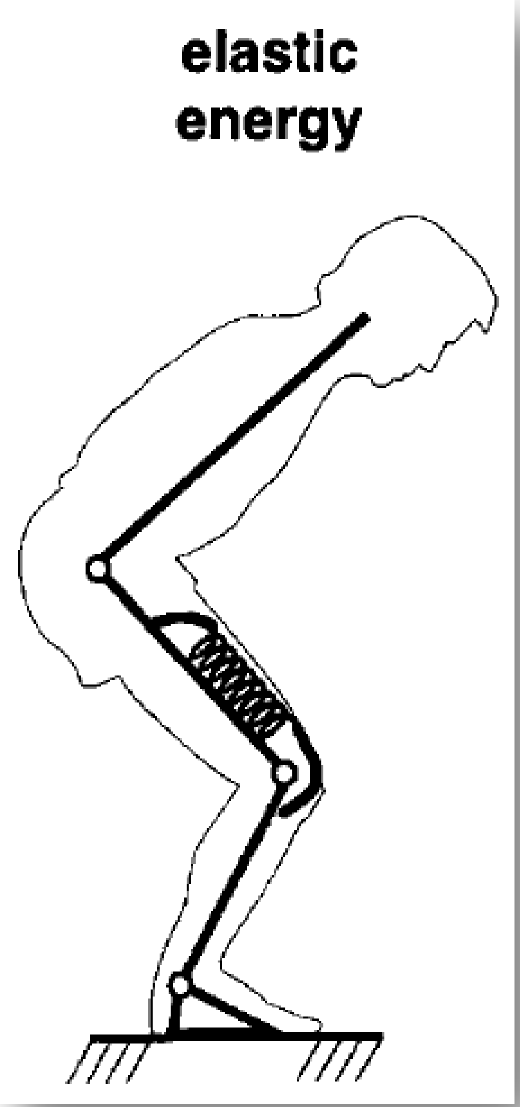


Muscle Coordination in Vertical Jumping:
A Case Study

Zajac, 1993

Analysis of Jumping

- Is elastic energy storage important to achieving maxium jumping height?
  - Storage in musculotendon elastic structures is NOT important
  - However, this storage does take place during propulsion
    - At least, 70% of plantarflexor energy delivered to the skeleton

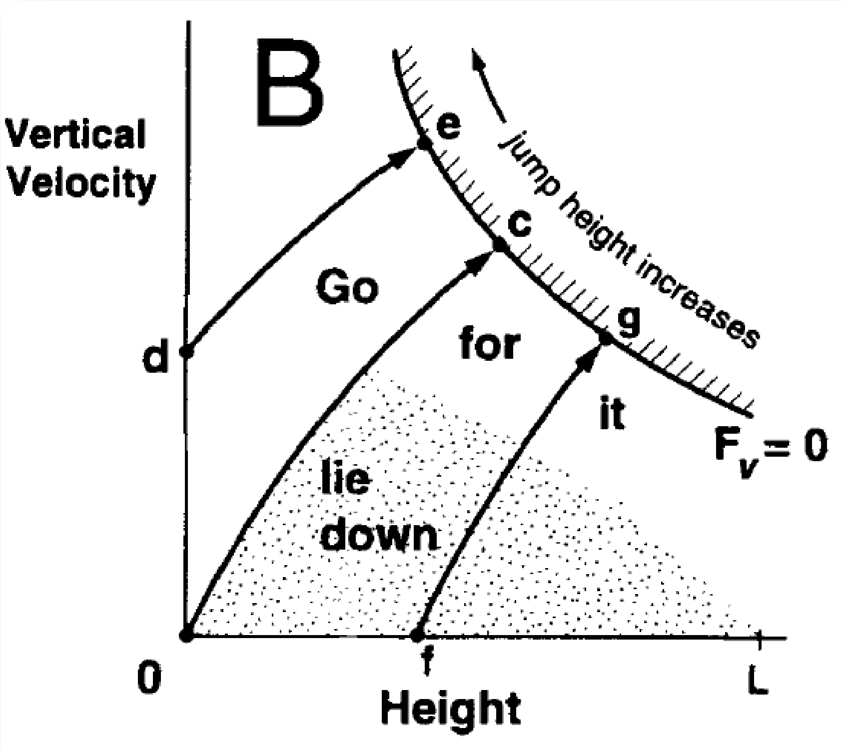


Muscle Coordination in Vertical Jumping: A Case Study

Zajac, 1993

Analysis of Jumping

- What is the purpose of the initial downward motion (countermovement) of the body?
  - It depends...
  - Increase take-off velocity by increasing propulsion time
    - GRF, extensor torque, and acceleration
  - Compensate for time to generate muscle force
  - Increase muscle strength with prior stretch

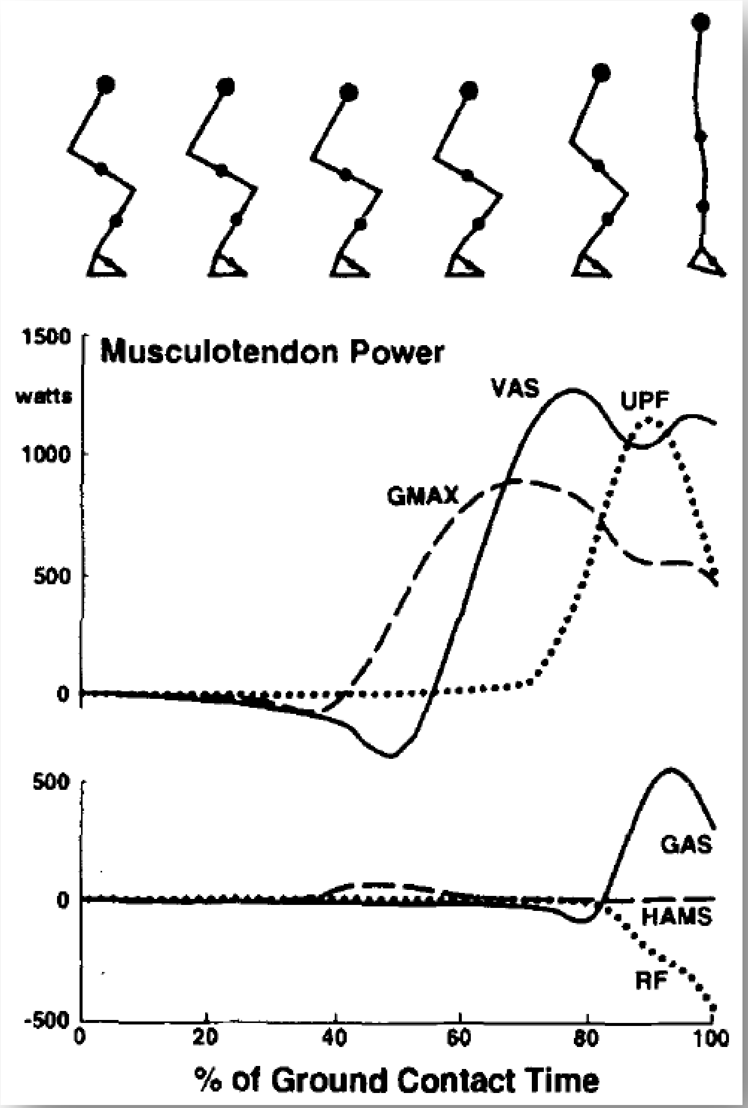


Muscle Coordination in Vertical Jumping: A Case Study

Zajac, 1993

Analysis of Jumping

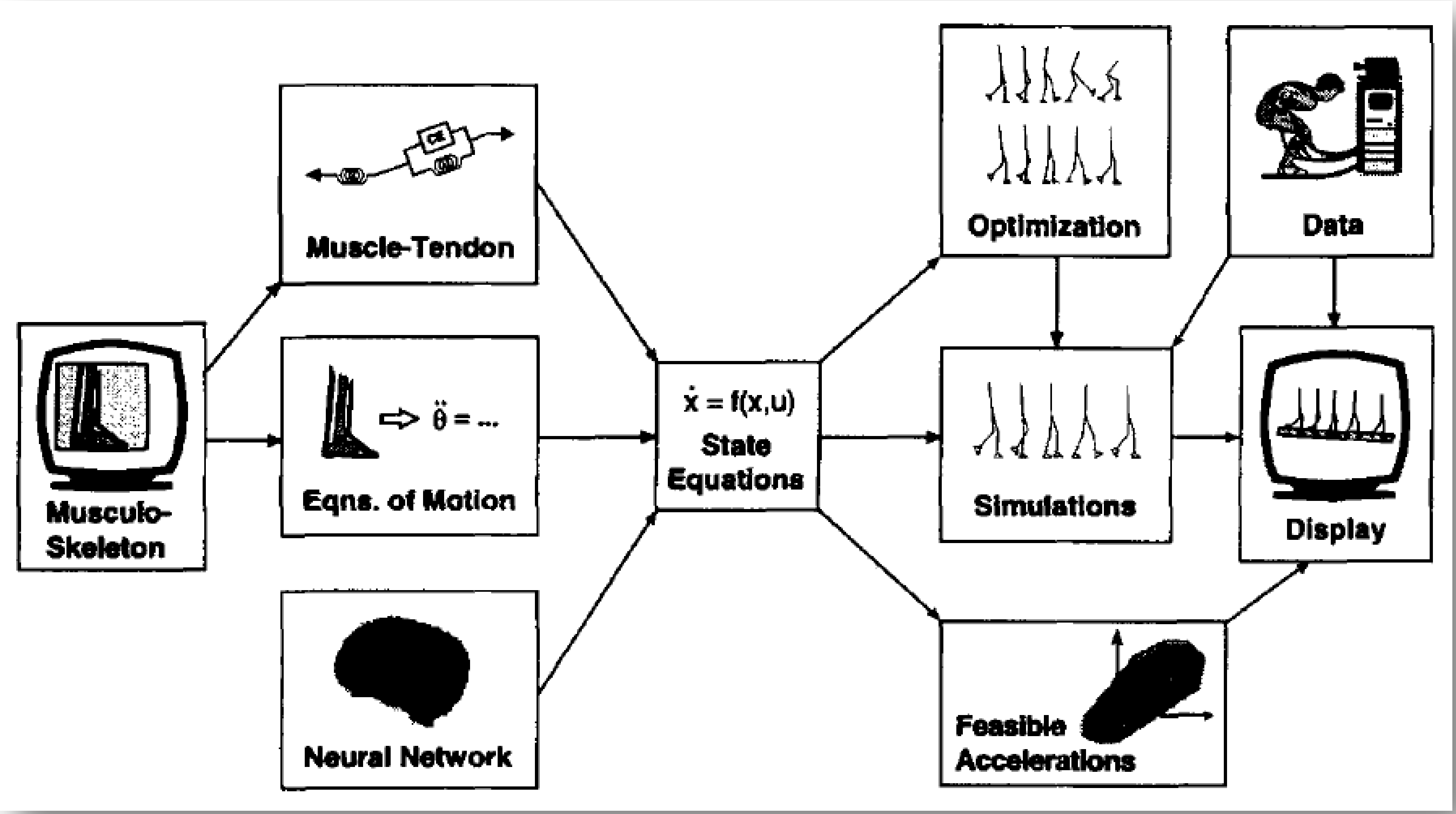
- What is the role of uniarticular leg muscles? Of biarticular leg muscles?
  - Uniarticular extensors provide propulsive mechanical energy
  - Uniarticular flexors do not
  - Biarticular muscles fine-tune the coordination



Muscle Coordination in Vertical Jumping: A Case Study

Zajac, 1993

Interactive Computer Workstation Environment



Why Not Use Simulation More?

- Considerable effort to develop and test models
- Difficult to find muscle controls
- Most biomechanical systems are unstable
- Subject-specific models are necessary
- We need BME 599

Summary

- Understanding muscle coordination in multijoint movement is complex because muscle forces affect many body segments
- Forward dynamics models provide an effective means to study muscle coordination
- Forward dynamics models usually need some kind of control (e.g., optimal control)
- Further work that combines models with experiments is needed to help elucidate coordination principles

Outline for Today

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Buchanan et al., 2004 vs. Erdemir et al., 2007

Similarities

- Both seek to “provide insight into neural control and tissue loading” and thus to “contribute to improved diagnosis and management of both neurological and orthopaedic conditions”
- Both discuss the use of musculoskeletal models and optimization
- Both discuss how to model muscle and tendon as well as musculoskeletal geometry
- Both discuss forward and inverse dynamics approaches for predicting muscle forces
- Both discuss the limitations of the approaches they present

Buchanan et al., 2004 vs. Erdemir et al., 2007

Differences

- Erdemir et al. focus on “optimization approaches” for predicting muscle forces, while Buchanan et al. focus on “EMG-driven approaches”
- Erdemir et al. use EMG data for model evaluation, while Buchanan et al. (2004) use EMG data for model calibration
- Buchanan et al. spend more time describing modeling of muscle activation and contraction dynamics than do Erdemir et al.

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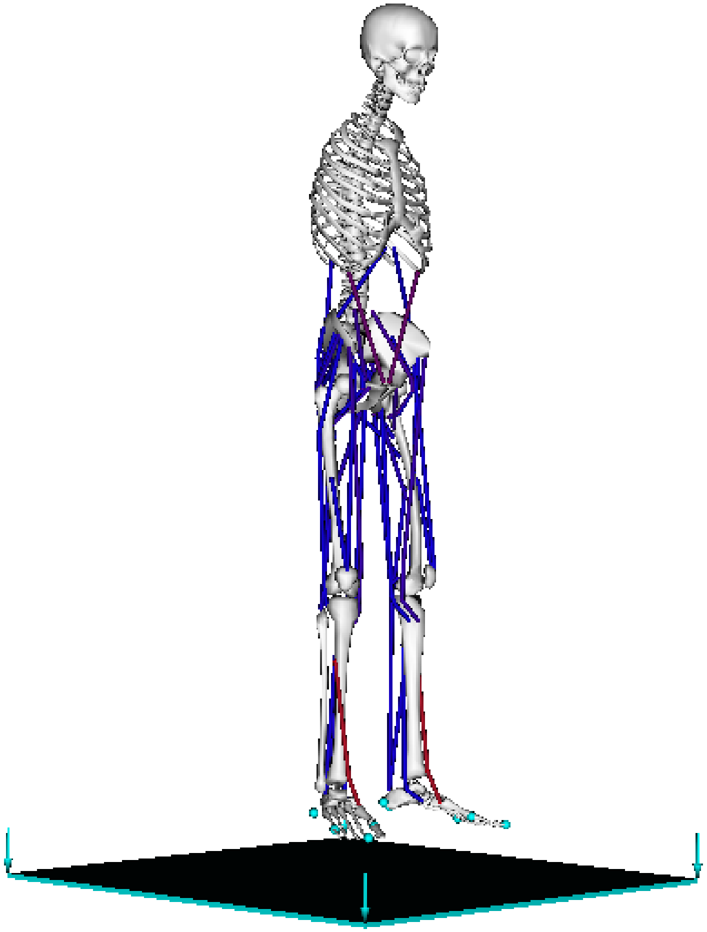
Simulation of Jumping



For Next Time…

- Read ***articles*** #6-8 of the Course Reader
  - ***Arnold et al., 2000***
  - ***Delp et al., 1999***
  - ***Blemker et al., 2007***
- Continue to think about topics for your ***individual research project***
- Continue working on ***Simulation Lab #1***! ***Due Jan 31***