Mechanical Engineering Seminar (U-Grad)
Special Topics in Mechano-Informatics II (Grad)
"Biomechanics of Human Movement"

May 23th, 2014

Dr. Emel Demircan

Announcements

- HW2 due today, 5pm **(Only Questions of I-IV)**
- Project Teams/Topics:

Socially Assistive Robots I:
1) Tomoyuki Maekawa
2) Emiko Uchiyama
3) Tianwei Zhang

Exoskeleton Robots & Rehabilitation Robotics:
1) Haruyuki Sanuki
2) Shunsuke Sato
3) Tatsuya Ichikawa

Socially Assistive Robots II:
1) Veerachant Srisamosarn
2) Park Huijun
3) Makoto Saito

Animation and Simulation:
1) Taira Miyatake
2) Yumiko Furuhata
3) Itsuki Ichikawa

Human Motion Tracking I:
1) Wu Cheng
2) Liang Boshen

Human Motion Tracking II:
1) Rie Hitsuyu
2) Heewon Park

Schedule

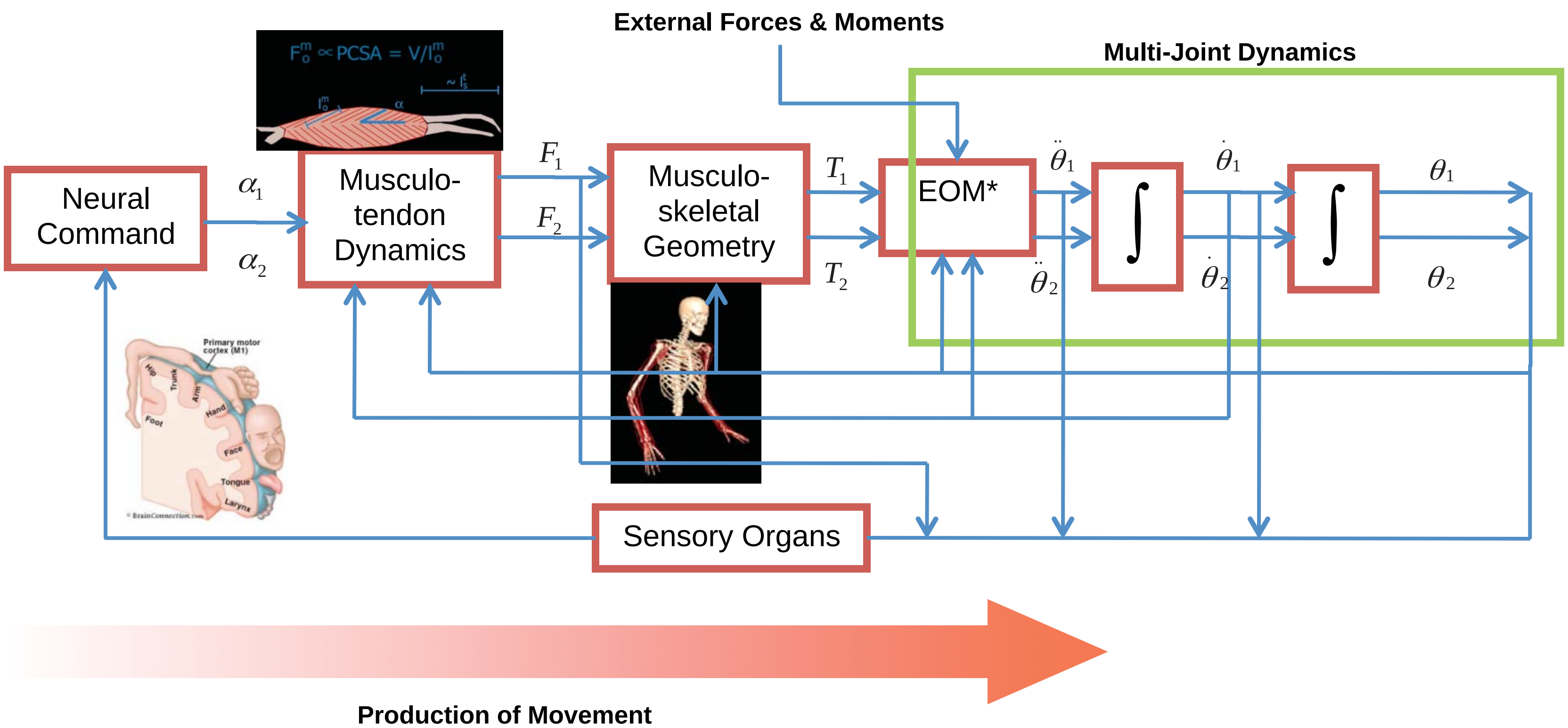
4/18: Introduction
4/25: Spatial Descriptions, Kinematics, Introduction to Biomechanical Simulation
5/2: Skeletal Muscle Structure, Force Generation, Musculoskeletal Geometry
5/9: Production of Movement
5/23: Motion Tracking Techniques
6/6: Inverse Dynamics, Control, Operational Space Formulation
6/27: Human Articulated Body Model, Dynamics, and Motion Control
7/4: Advanced Topics in Human Motion Analysis, Student Presentations

Agenda

- Optometric Methods in Human Motion Analysis
  - Historical Development
  - Basics of Human Gait
  - Non-Optical Methods
  - Optical Methods
  - Related Measurements (Force Plates, EMG)
  - Data Processing, Analysis, and Display
- Inverse Kinematics and Inverse Dynamics in OpenSim
- Operational Space Formulation
  - Operational Space Dynamics
  - Operational Space Control
  - Human Motion Reconstruction using Operational Space

From Neural Command to Motion

Human Motion Production

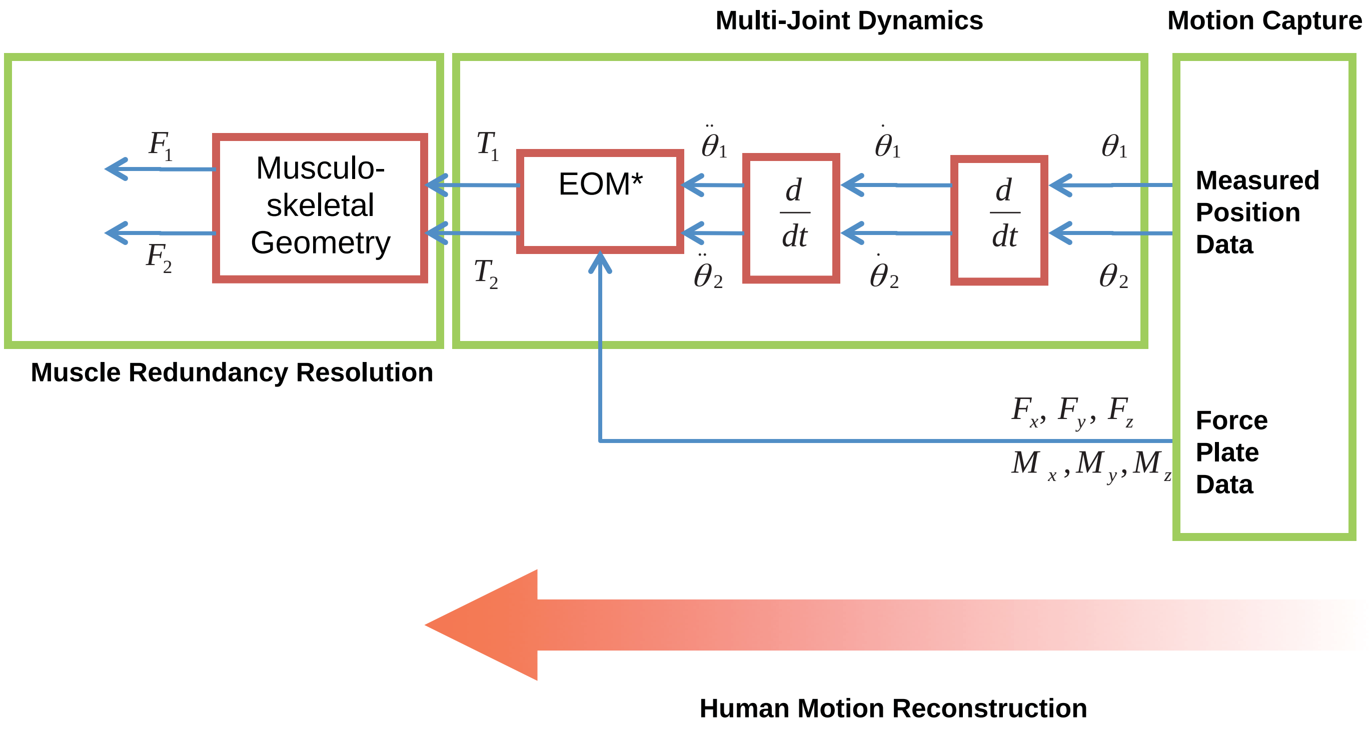


(Adapted from: Buchanan et al. 2004. Neuromusculoskeletal modeling: estimation of muscle forces and joint moments and movements from measurements of neural command. Journal of Applied Biomechanics)

**: equations of motions*

Motion Capture Systems

Human Motion Reconstruction



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- **Optometric Methods in Human Motion Analysis**
  - **Historical Development**
  - **Basics of Human Gait**
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Optometric Methods in Human Motion Analysis

Historical Development

- Non-quantitative visual observations
- Gait: only cadence & stride length could be measured
- Borelli, 1679 stressed the need for measurement (force)

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Motion Capture Systems

History of Movement Science

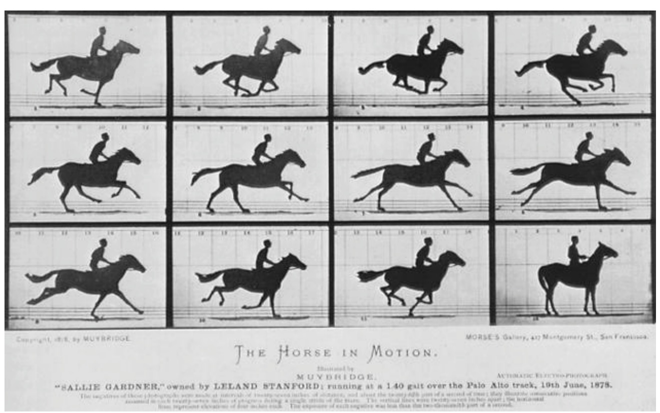
1543: Andreas Vesalius publishes the first illustrated systematic anatomical atlas of the human body.

1872: former Governor of California **Leland Stanford**, had taken a position on a popularly-debated question of the day: whether all four of a horse's hooves left the ground at the same time during a gallop.

1877: Muybridge settles the bet with a single photographic plate showing Occident, Stanford's own racehorse, with all feet in the air. By **1878**, **Muybridge** had successfully photographed a horse in fast motion using a series of twenty-four cameras

1887: Etienne Jules Marey invents the "chronophotograph"

1894: Etienne Jules Marey invents the first slow motion camera

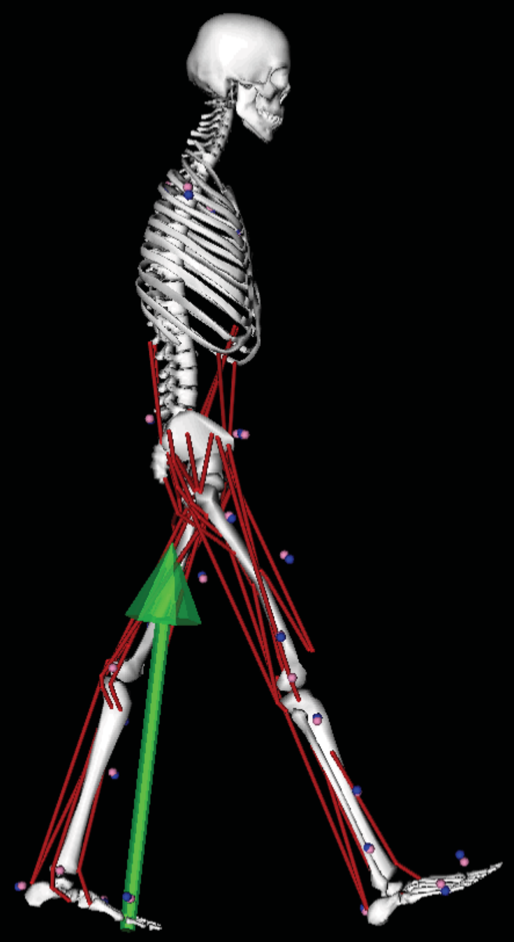


" No natural phenomenon can be understood without carefully considering how it emerged"
N. A. Bernstein, " On Dexterity and Its Development", 1996.

Optometric Methods in Human Motion Analysis

Basics of Human Gait

balance | weight bearing | forward propulsion



Gait Terminology

Stride: complete cycle of locomotory movement

- sequence of right plus left steps

Step Length : distance between R and L heel strikes

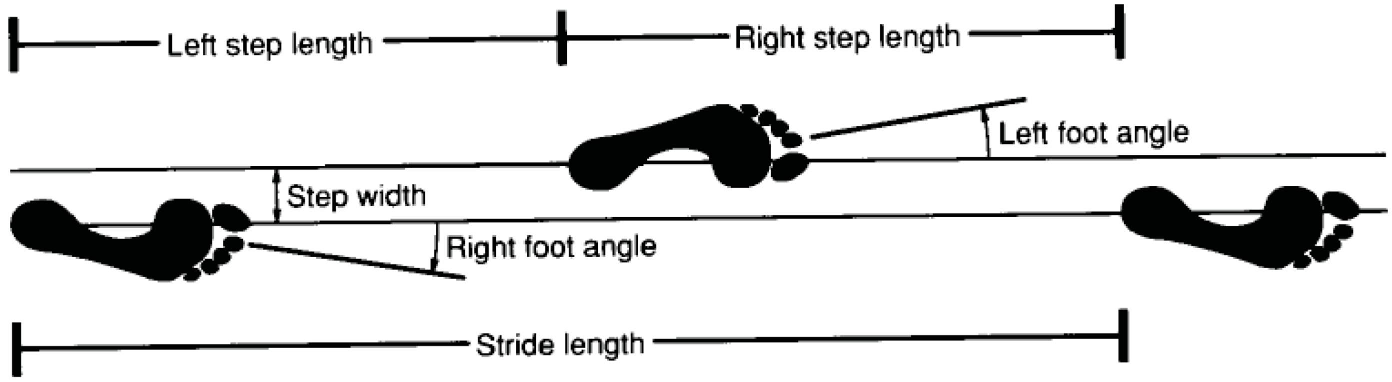
- normal adult step length : 80 cm

Cadence: rhythm of locomotion

- normal adult cadence: 101-120 steps/minute

Walking Velocity = cadence * step length

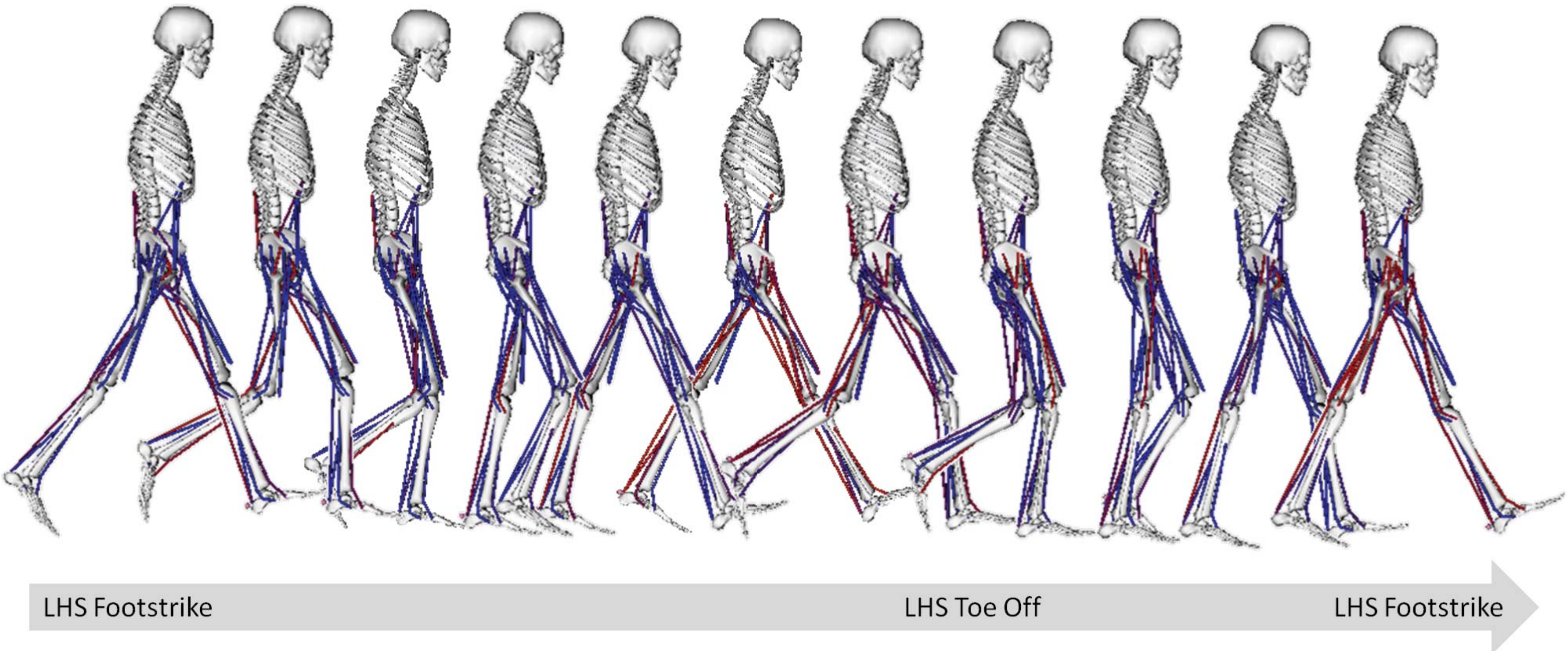
- normal adult walking velocity:1.5 m/s



Clinical biomechanics of gait, Stephen Robinovitch

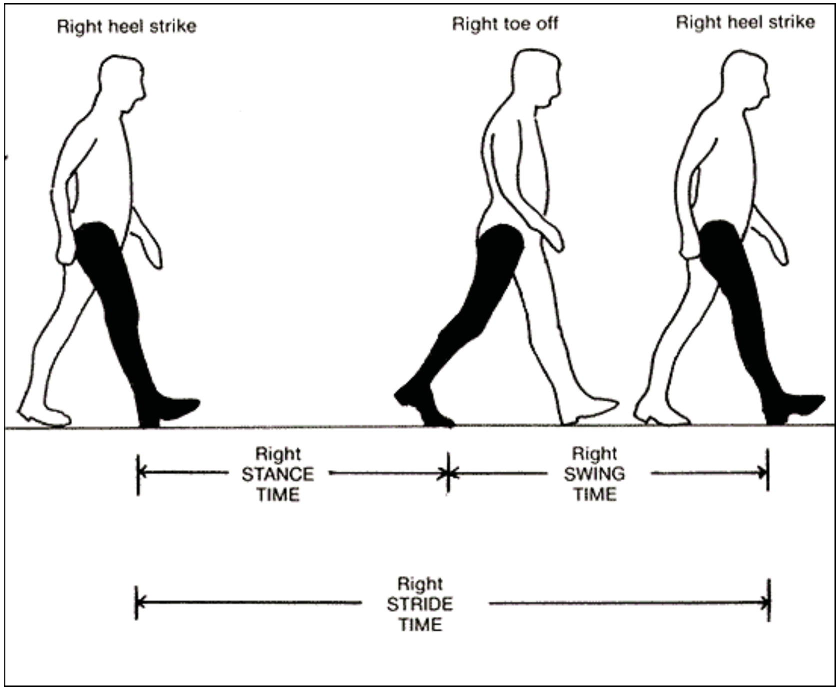
Gait Cycle

The gait cycle is the basis for understanding normal and pathological human walking



Gait Cycle

Stance phase takes up 60% of the stride
Swing phase takes up the remaining 40%



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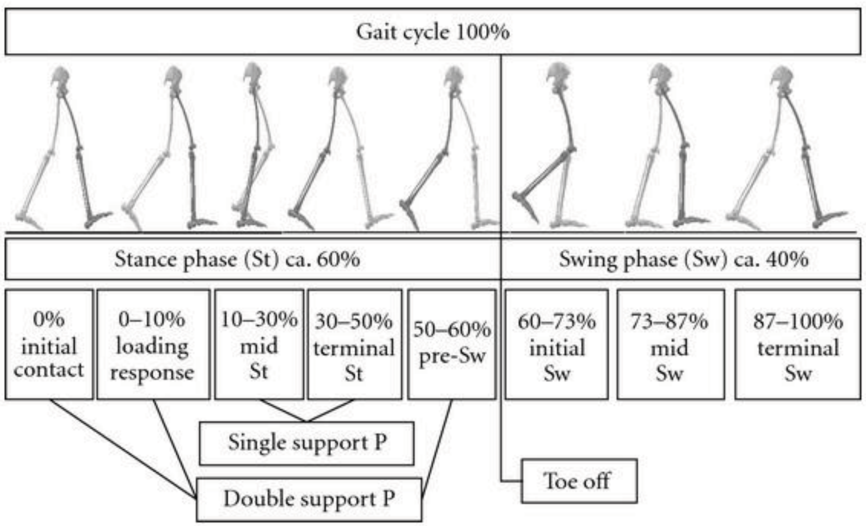
Gait Cycle

Stance begins and ends with periods of double support



http://www.jeios.com/spler/wp-content/uploads/2014/01/Kinematics.jpg

Gait Variables

Temporal Variables:

- Cadence
- Speed
- Stride length
- Stride width

Can also be considered as **kinematic variables**

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Kinematic Variables:

- Joint angles (sagittal and coronal planes)
    - 2D gait analysis: only angles in the sagittal planes (i.e., angles of the trunk, pelvis, flexion and extension of hip, knee, and ankle)
    - 3D gait analysis: angles in both sagittal and coronal planes

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Kinetic Variables:

- Directly measured variables: ground reaction forces
- Calculated variables: numerical processing of the kinematic variables

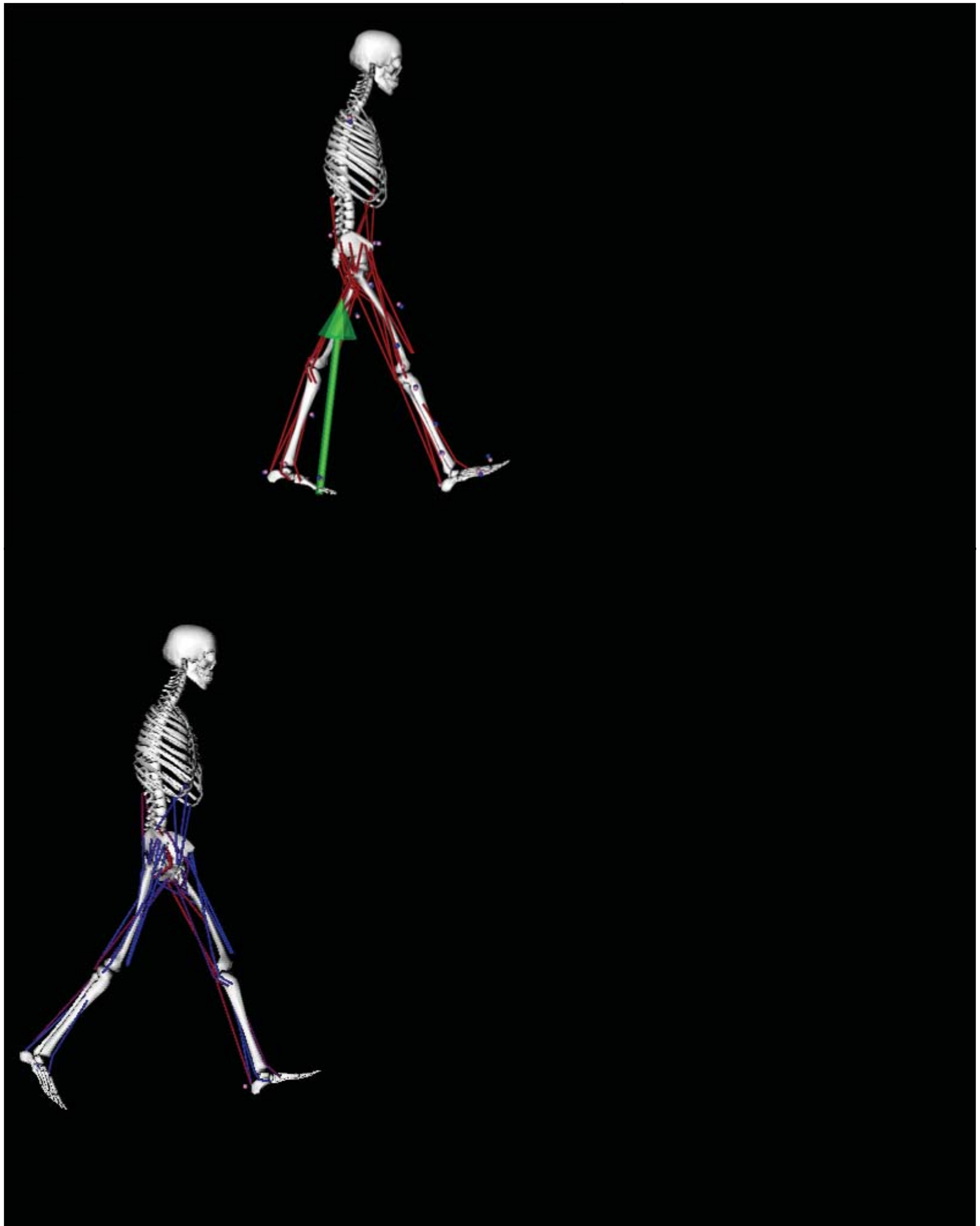
Combined, used to drive the **joint moments** (inverse dynamics)

Gait: Experiment and Simulation

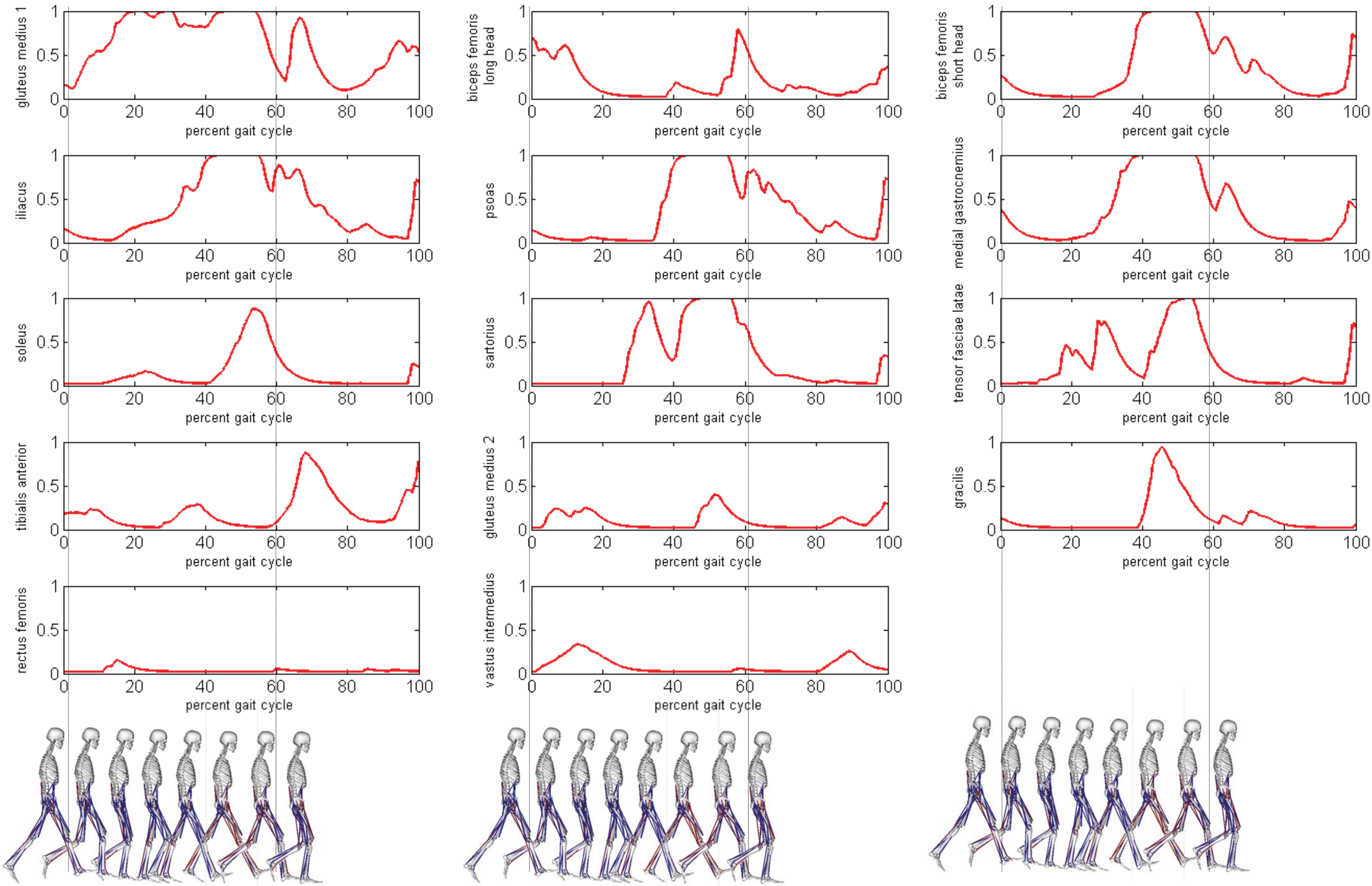
Healthy Male
Free Speed (1.75m/s)

- Motion Capture
- Force Plate
- Electromyography

23DOF actuated by
92 muscle-tendon units



Muscle Activations during Normal Gait (1.75m/s)



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EMG-informed Computed Muscle Control for Dynamic Simulations of Movement

Project Overview

Overview
Statistics
Geography of use

Team

Downloads

Documents

Publications

Public Forums

Advanced

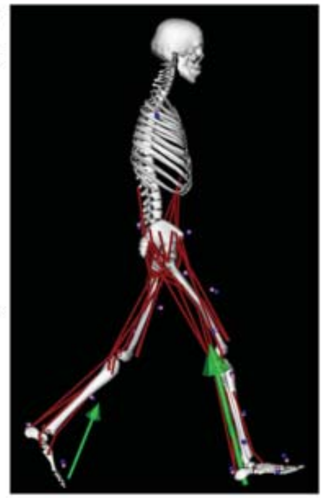
Downloads & Source Code

EMG-informed CMC

This project also makes **source code** available.

Description: This project is an EMG-informed control plug-in that interfaces with OpenSim to provide robust estimates of muscles activation patterns.

Available Downloads and Their Potential Uses: This project contains the motion capture, force plate, EMG data of a normal human walking together with the three-dimensional simulations (IK, RRA and CMC results) and the human model. To download the simulations and associated documentation, please see the Downloads section of this project. Please see



https://simtk.org/home/opensim for more information on OpenSim and its branch /Branches/JasonEmel485Project/ in order to reproduce or modify the simulations . These simulations were generated using OpenSim version 1.5, which is the software version we recommend to those using these simulations.

Purpose/Synopsis: Develop a modified version of Computed Muscle Control (CMC) based on filtered EMG data to track the desired muscles and to create dynamic simulations of movement.

Audience: Users interested in analyzing human movement through EMG-based muscle activation patterns.

Project Lead

Emel Demircan
Contact

Driving Biological Problems

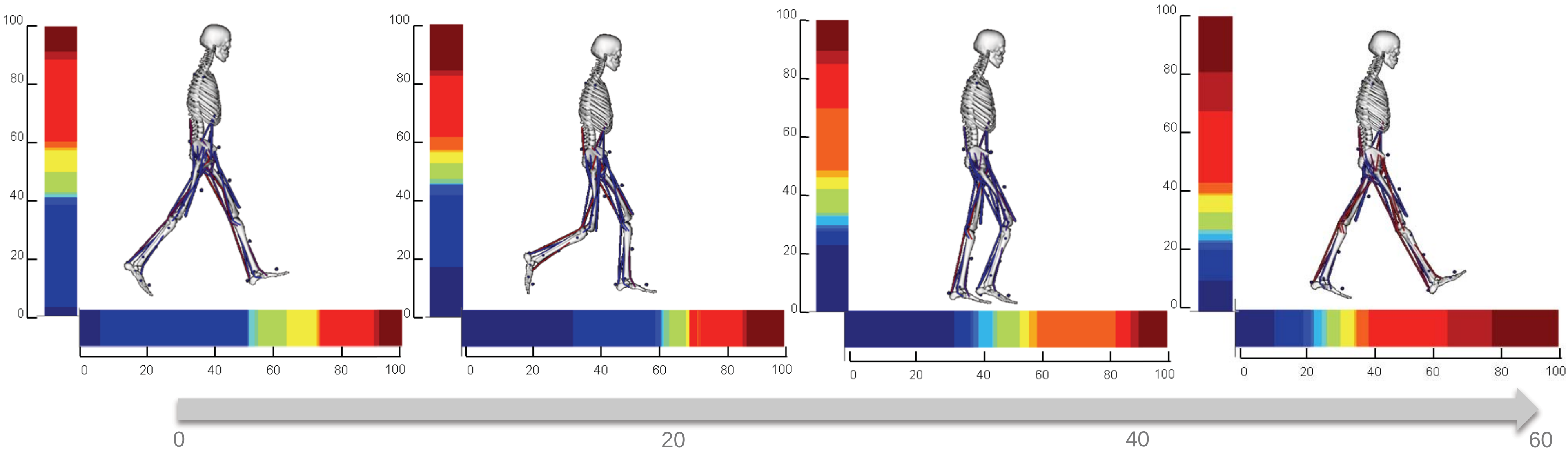
This project is part of

Neuromuscular Biomechanics

Demircan E., Wheeler J., Anderson F. C., Besier T., and Delp S., “EMG-Informed Computed Muscle Control for Dynamic Simulations of Movement.” In *Proc. of the* ***XXII Congress of the International Society of Biomechanics***, Cape Town, South Africa, July 2009

Constraint-Consistent Analysis of Muscle Force Contributions to Human Gait

$$\ddot{x} = J(q)A(q)^{-1}(L^T m_{max} a - g(q) - J_{c_1}^T F_{ext_1} - J_{c_2}^T F_{ext_2})$$



Results	Our findings	Liu et al. 2006	Neptune et al. 2004	Liu et al. 2008
Gluteus medius, vasti, hamstrings, gastrocnemius, soleus and dorsiflexors are important modulators of accelerations	✔	✔	✔	✔

Demircan, E. and Khatib, O., "Constraint-Consistent Analysis of Muscle Force Contributions to Human Gait", Advances in Robot Kinematics, Springer, 13th International Symposium, Innsbruck, Austria, June 2012

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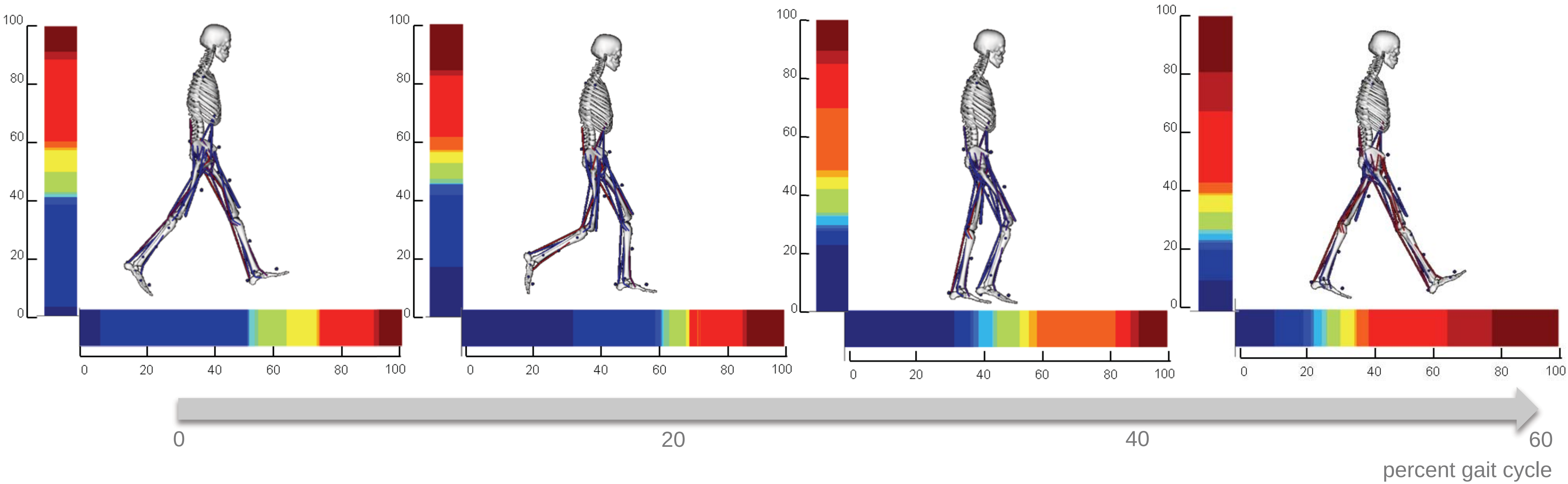

Results	Our findings	Liu et al. 2006	Neptune et al. 2004	Liu et al. 2008
Hamstrings and gluteus medius were primary contributors to support and progression in early stance.	✔	-	-	✔

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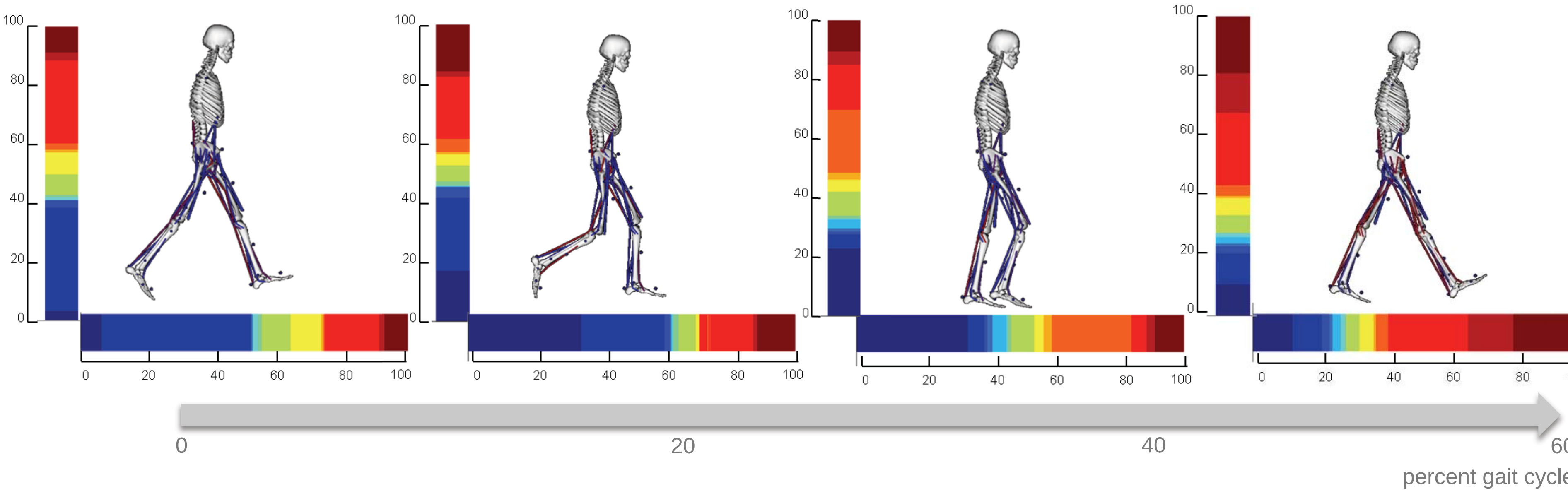

Results	Our findings	Liu et al. 2006	Neptune et al. 2004	Liu et al. 2008
At faster speed, greater forces in the soleus and gastrocnemius are observed in late stance.	✔	-	-	✔

Demircan, E. and Khatib, O., “Constraint-Consistent Analysis of Muscle Force Contributions to Human Gait”, Advances in Robot Kinematics, Springer, 13th International Symposium, Innsbruck, Austria, June 2012

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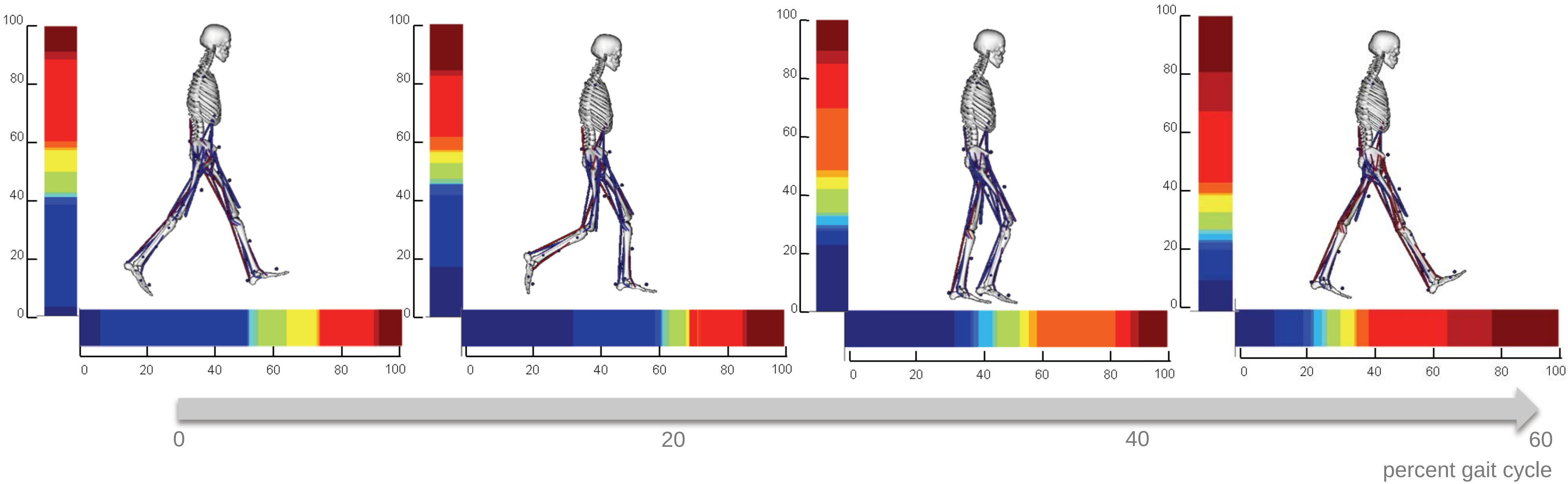
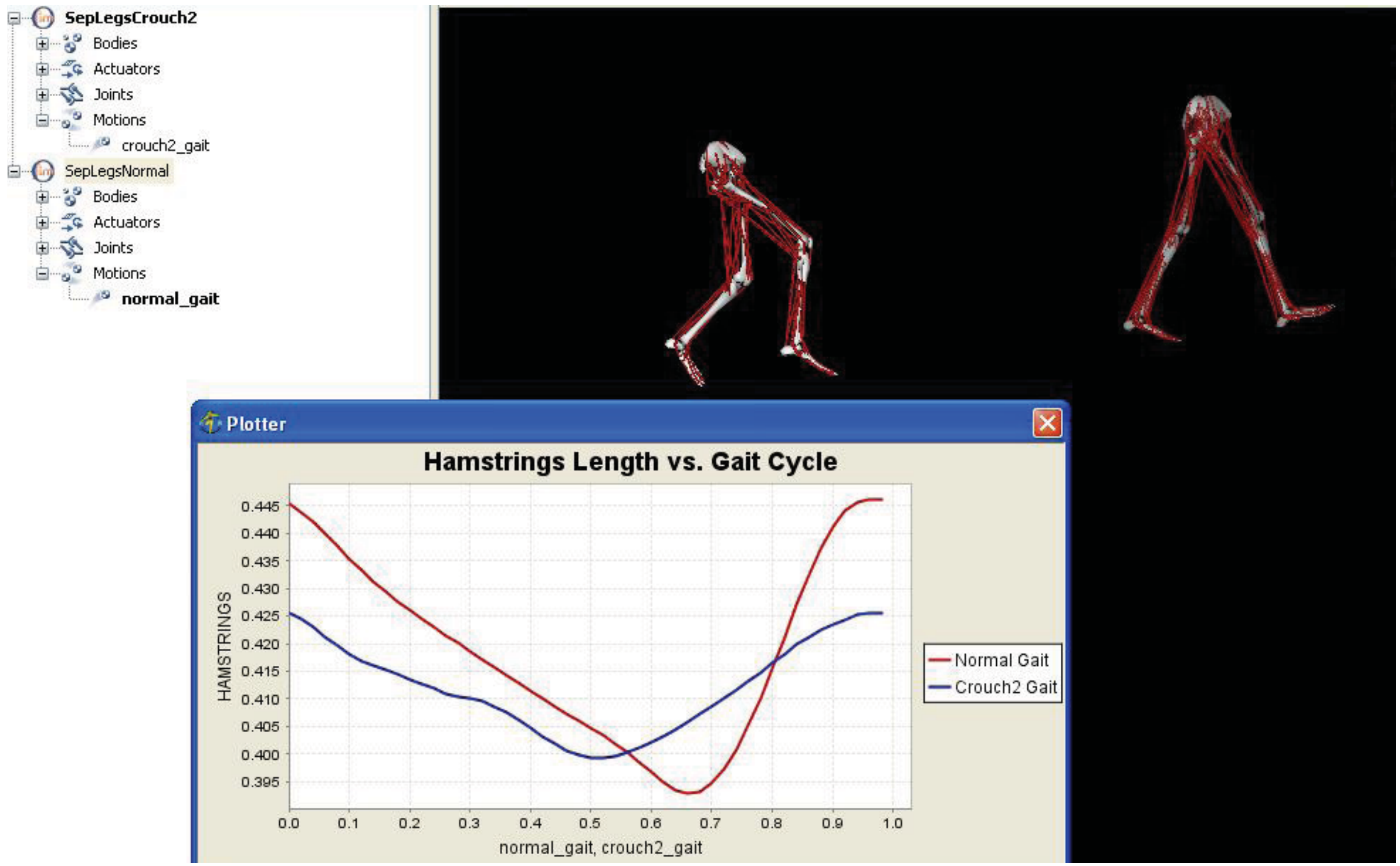


Results	Our findings	Liu et al. 2006	Neptune et al. 2008	Liu et al. 2008
Hip flexors (iliacus, psoas, rect fem) didn't contribute significantly to mass center acceleration.	✔	-	✖	✔

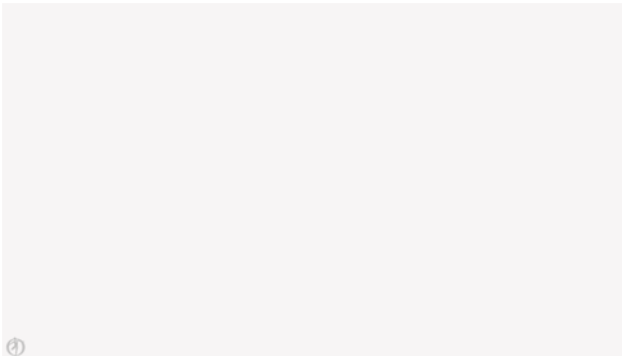
Demircan, E. and Khatib, O., "Constraint-Consistent Analysis of Muscle Force Contributions to Human Gait", Advances in Robot Kinematics, Springer, 13th International Symposium, Innsbruck, Austria, June 2012

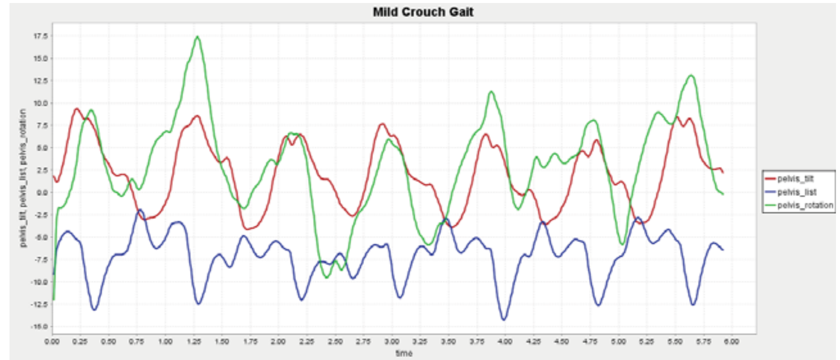
Musculoskeletal Disorders
Crouch vs. Normal Gait

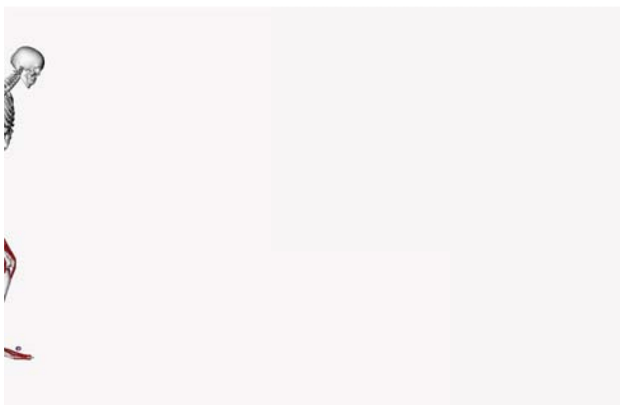


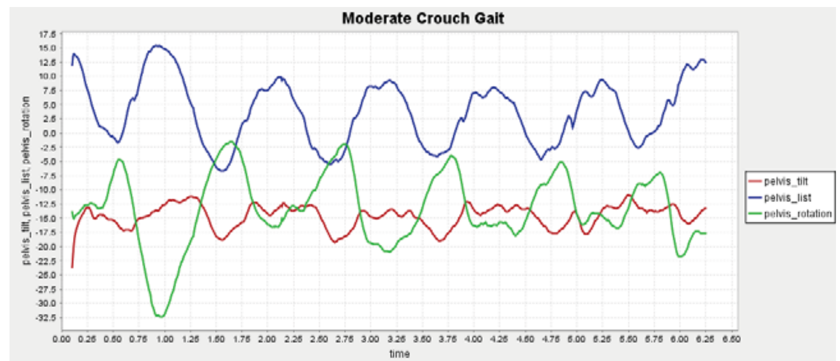
Professor Scott Delp – Department of Bioengineering
Professor Jessica Rose - Stanford Children Gait Hospital
Department of Orthopeadic Surgery, School of Medicine

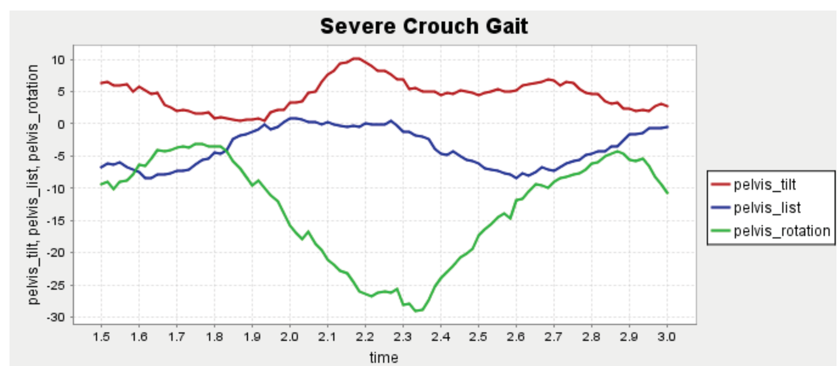
Reeducation of Musculoskeletal Disorders







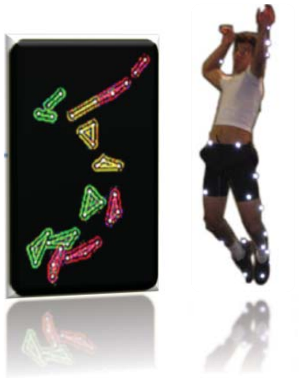




Motion Capture Systems

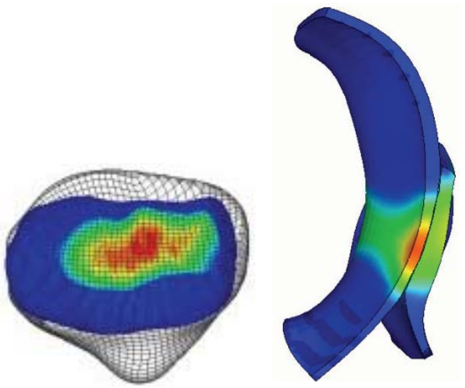
Tools to Study Human Movement

- Biomechanical tools:
  - Musculoskeletal models



- Experimental tools:
  - Motion capture systems
  - Force plates and EMG
  - Animal studies

- Mathematical tools:
  - Finite element methods
  - Multi body dynamics algorithm



Motion Capture Systems
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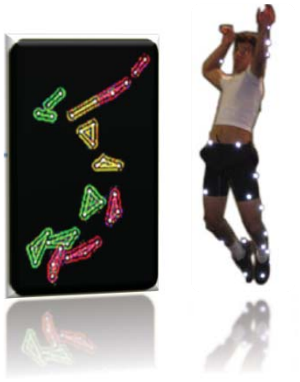

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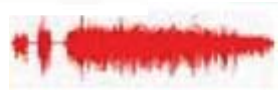

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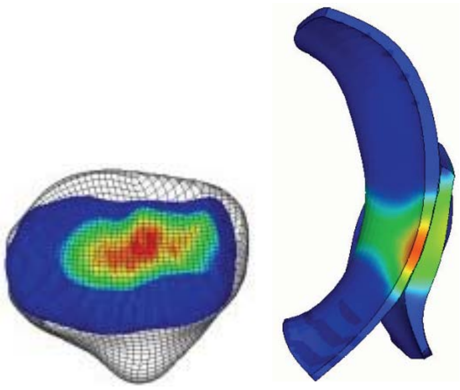


- Mathematical tools:
  - Finite element methods
  - Multi body dynamics algorithm

Optometric Methods in Human Motion Analysis
Non-Optical Methods

- Goniometry: directly measures the angles between the segments (i.e., joint angles)

- Accelerometry: directly measures the accelerations

Optometric Methods in Human Motion Analysis

Non-Optical Methods

Method	**Advantages**	**Disadvantages**
Goniometry	• Cheap • Lightweight • Possible to use for remote activities (e.g. skiing)	• Cannot make absolute measurements • Sensitive to mounting error • Generally 2D • Electronic devices require electrical power and cables to be attached to subject
Accelerometry	• Very Sensitive • Very Accurate Devices • Velocity and Position obtained by integration • Can get 3D motion measurement	• Sensitive to mounting/ placement • Delicate • Expensive • Suffers from drift • Needs min. 6 per segment • Requires electrical power and cables

Optometric Methods in Human Motion Analysis

Optical Methods | Marker-based (Mocap)

Light Sources and Markers:

- Active or Primary Markers (LEDs)
- Passive or Secondary Markers (retroflective)

Optometric Methods in Human Motion Analysis

Optical Methods | Marker-based (Mocap)

Method	Advantages	Disadvantages
Active Markers (LEDs)	• Each can be identified automatically by fast, sequential illumination (multiplexing)	• Synchronization problems (need post-processing) • Require electrical supply and cabling on the subject • Relative narrow viewing angle
Passive Markers	• Do not require electrical supply or cabling on the subject • No limitation of viewing angle	• Automatic identification by multiplexing is not possible

Optometric Methods in Human Motion Analysis
Optical Methods | Marker-based (Mocap)

- Passive markers (retroflective)
- Accurate 3D position data,
- Easy to use, continuous whole-body sensing,
- Synchronize with contact force, muscle activity data.

Optometric Methods in Human Motion Analysis

Optical Methods | Marker-based (Mocap)

Sampling rate:

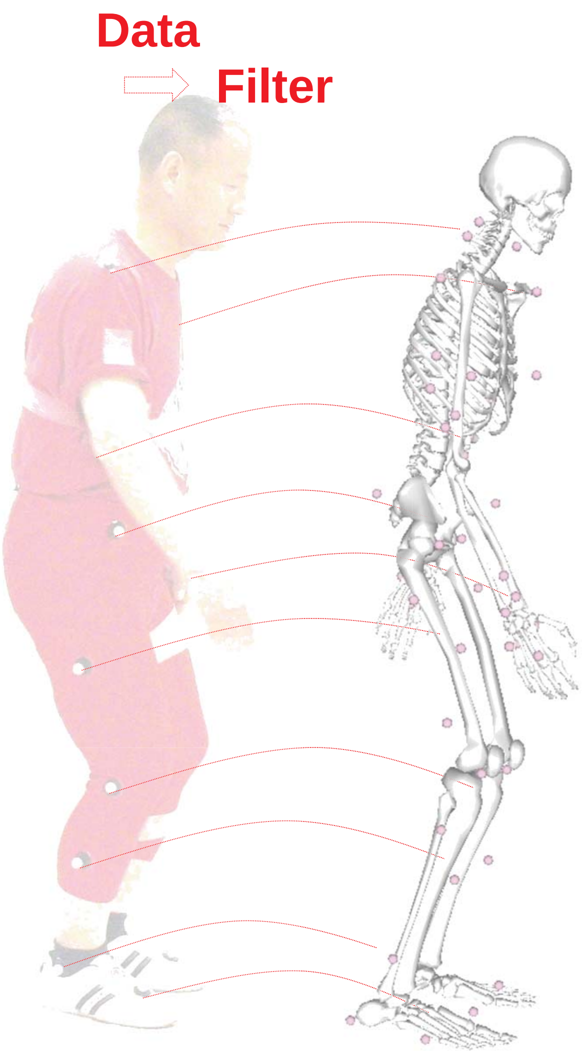
- Sampling marker positions at a fixed rate (i.e., sampling rate)
- Depends on the movement to be studied: Walking (25-30Hz)
- It is the **frequency content** of a movement that determines the required sample rate**, not the speed**

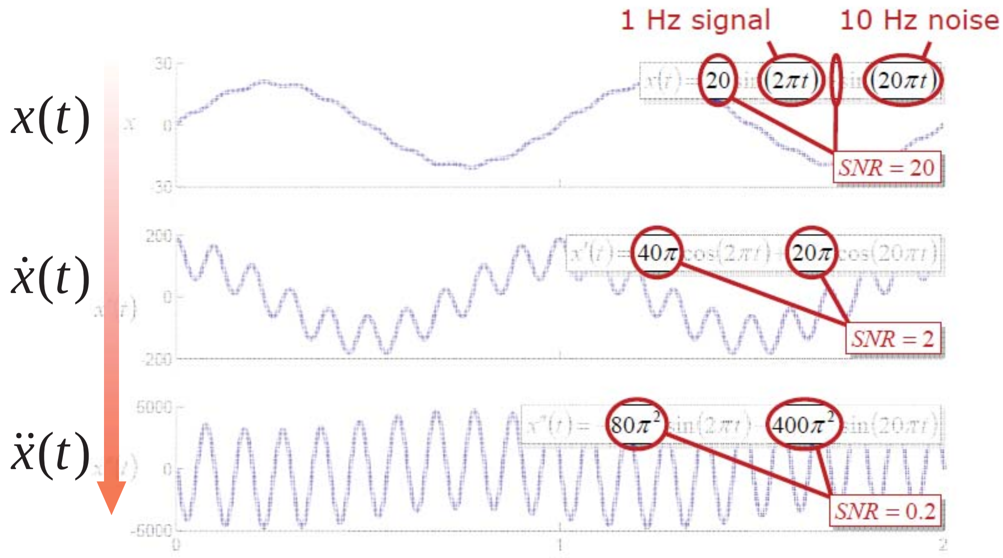
Example:

Fastest movements in walking (foot during middle swing phase) can be accurately measured at **low sampling rates**

Sudden changes of the direction of movement of the heel at foot strike (although occurring at a slower speed) need a **higher sampling rate** (i.e., over 100Hz) for accuracy

Smoothing Data

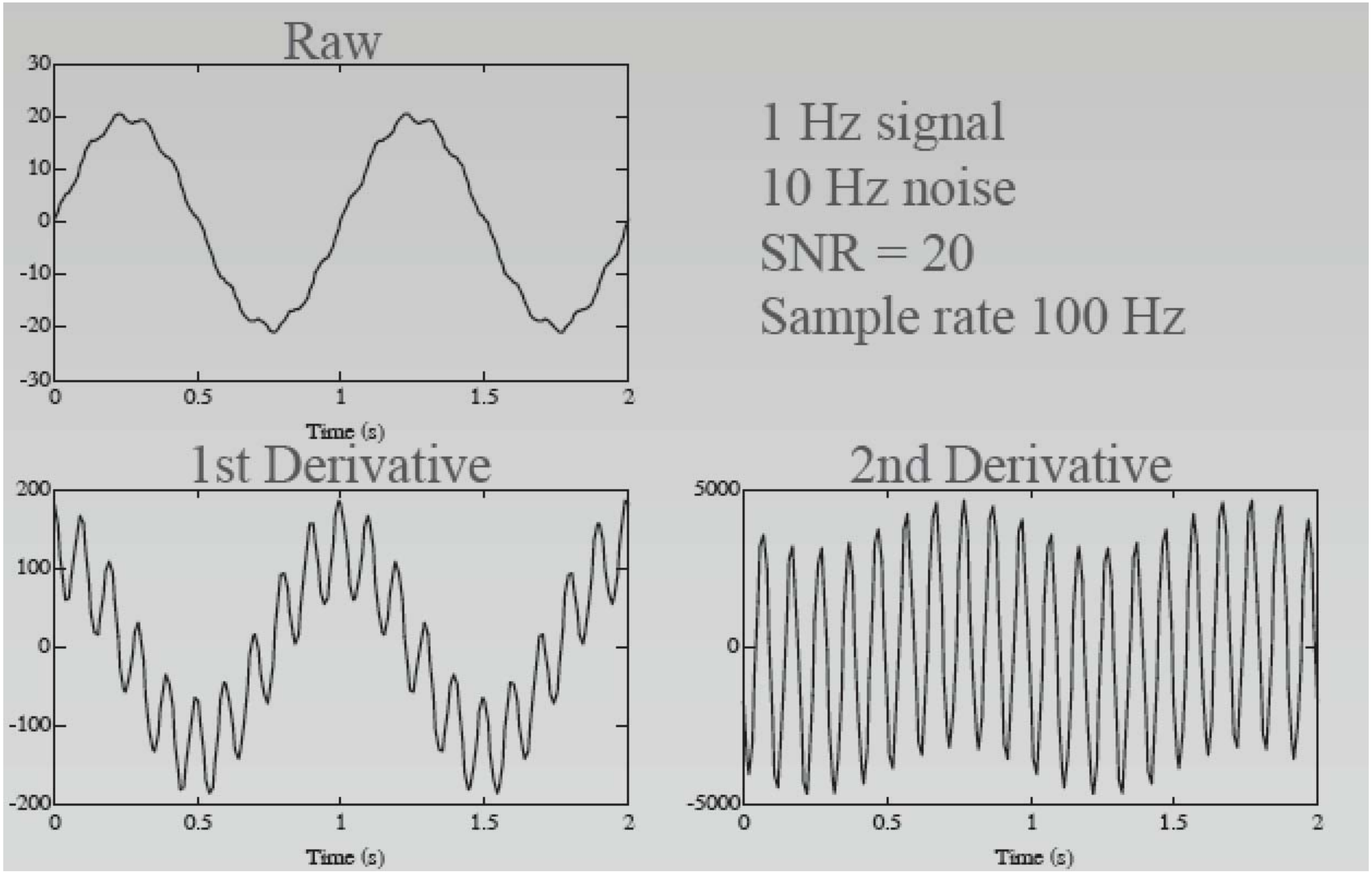




Differentiation amplifies high-frequency noise

Smoothing Data

Example of Noisy Data



Smoothing Data

Differentiation of Noisy Data

Consider a 1 Hz signal contaminated with 10Hz noise, with a signal-to-noise (SNR) ratio of 20:

$$x(t) = 20\sin(6.28t) + \sin(62.8t); \quad \text{SNR} = 20$$

$$x'(t) = 125\cos(6.28t) + 62.8\cos(62.8t); \quad \text{SNR} = 2$$

$$x''(t) = -785\sin(6.28t) - 3944\sin(62.8t); \quad \text{SNR} = 0.2$$

The 2nd derivative of the noise is 5 times larger than the 2nd derivative of the signal!

Smoothing Data

Noise Characteristics

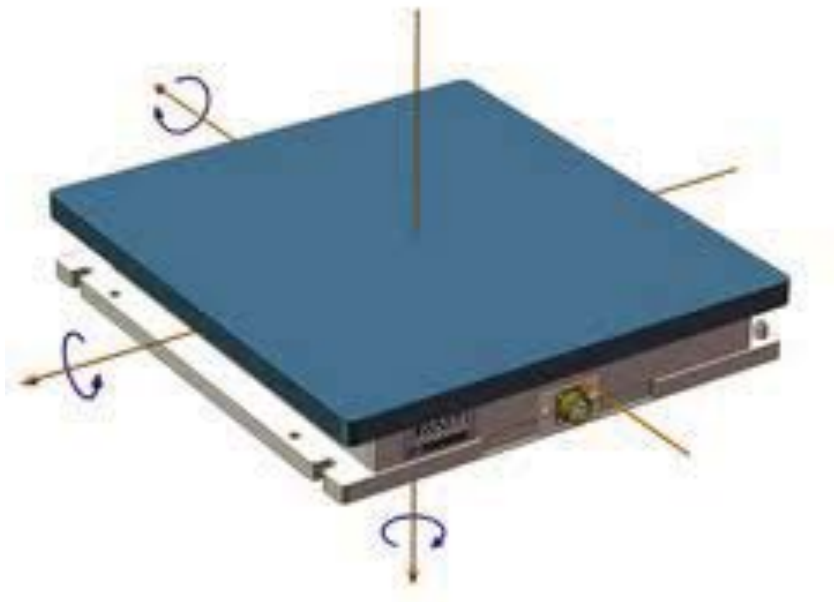
Noise Source	Duration (ms)	Frequency Range (Hz)
Skin movement artifact	100-200	1-10
Partially obscured markers, interpolation errors	Several frames	Varies
Camera switching, tracking errors	1 or more frames	High (step)
Camera/digitizer noise	Continuous	Broadband (white)
Electrical interference	Intermittent (spike) or continuous	Usually high

Optometric Methods in Human Motion Analysis

Related Measurements

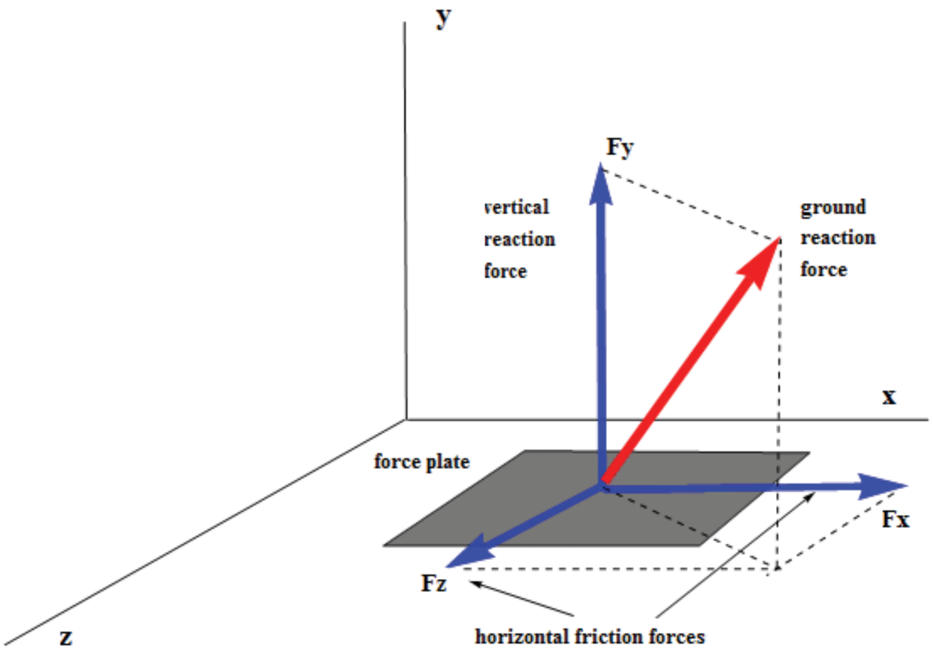
- Force Plate (ground reaction forces)
- Electromyography (muscle activity)
- Force Sensors (contact forces)

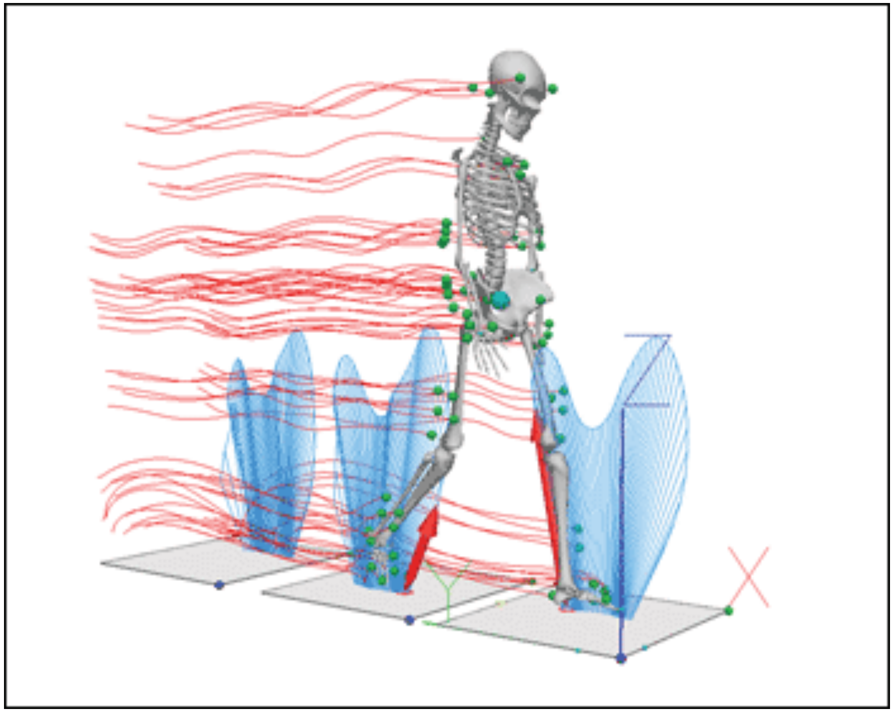
Force Plates



Ground Reaction Forces during Normal Gait

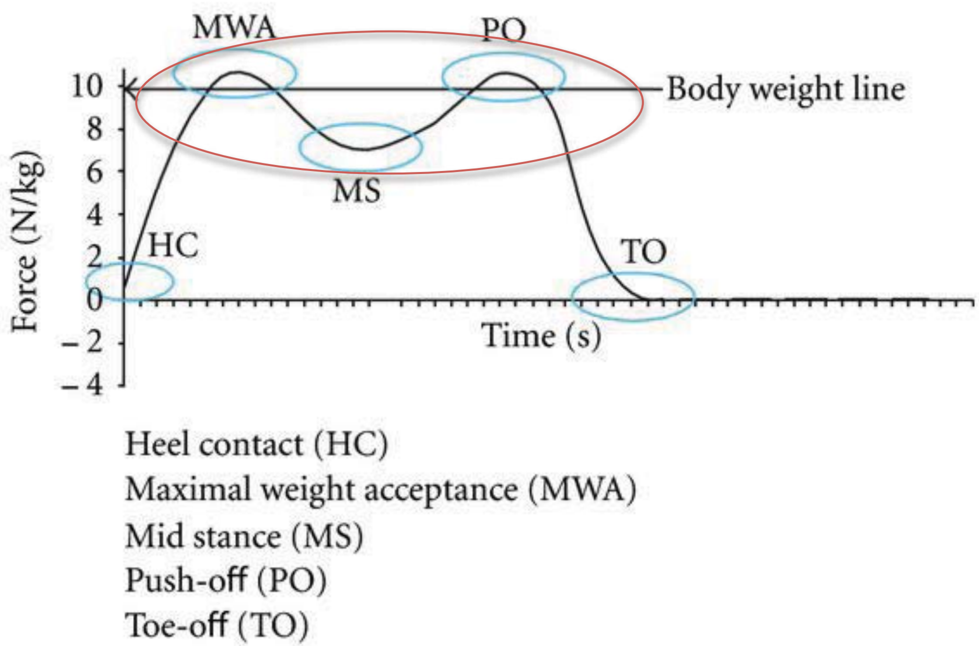
Information from the force plates
Fx, Fy, Fz & Mx, My, Mz





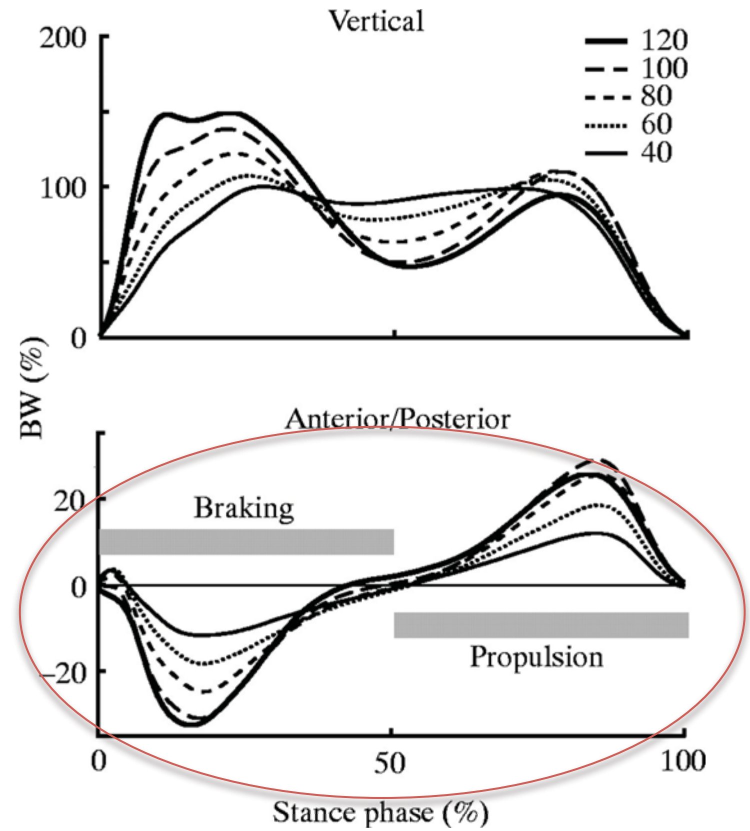
http://www.sheffield.ac.uk/research/impact/stories/fce/5

Ground Reaction Forces during Normal Gait



http://www.hindawi.com/journals/rerp/2011/586412/fig4/

Vertical GRF goes above and falls below body weight



Ankle plantar flexor force production is an important determinant of the preferred walk-to-run transition speed, J Exp Biol, March 2005

Horizontal GRF pushes back at initial contact and forward at the end of single stance.

Electromyography

Electromyography: Recording of electrical signals from the muscles during activity

Electromyogram (EMG): Recorded signal

Non-invasive (surface electrodes)

Invasive (needles or fine wire electrodes)

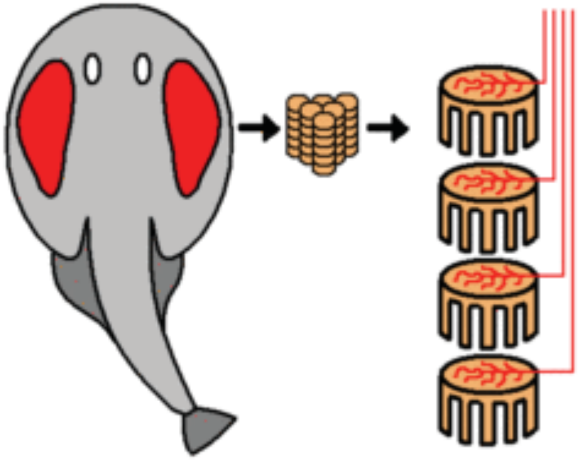
Electromyography

Historical Development

Francesco Redi (1626-1698)

- First to recognize connection between muscles and generation of electricity.
- 1666—documented that electric ray fish used a highly-specialized muscle.
- Most famous for establishing that maggots do not spontaneously generate from rotting meat.

Picture Source: http://www.liberliber.it/biblioteca/r/redi/



wikipedia

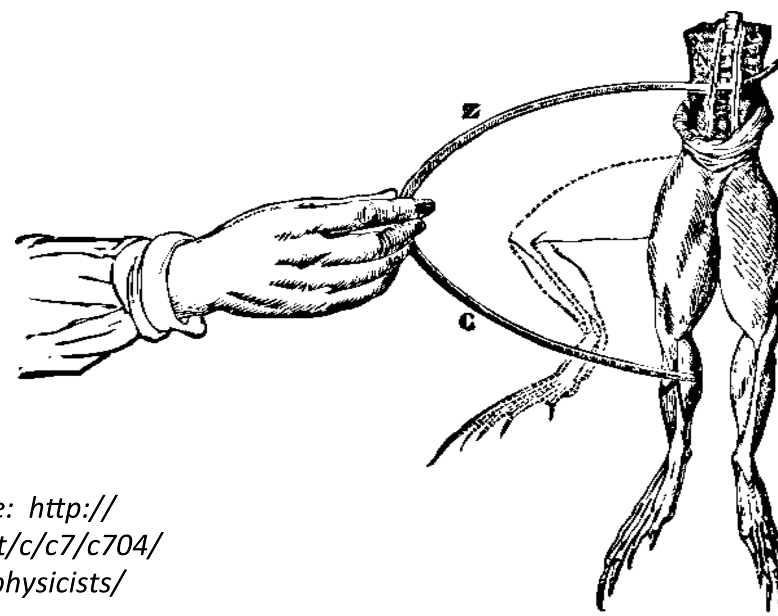
Electromyography

Historical Development

Luigi Galvani

- Credited as the father of neurophysiology for his work with frogs' legs—1791 (animal electricity)
- Showed that "electrical stimulation of muscular tissue produces contraction and force."
- Because of limited instrumentation, his work was not fully accepted until almost 40 years later.

Picture Source: http://info.uibk.ac.at/c/c7/c704/museum/en/physicists/galvani.html

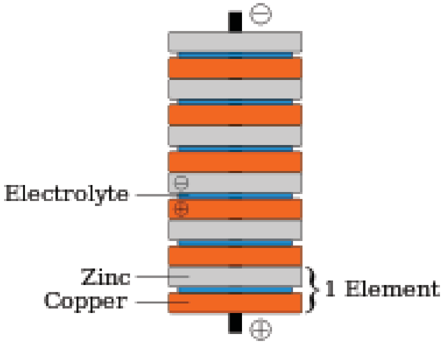


Picture Source: http://butler.cc.tut.fi/~malmivuo/bem/bembook/01/01.htm

Electromyography
Historical Development

Alessandro Volta (1745-1827)

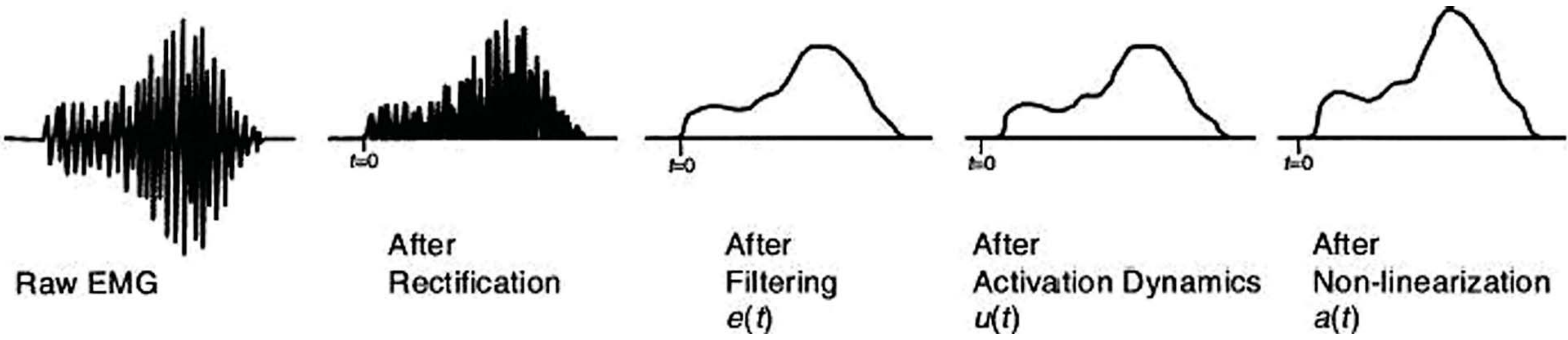
- Replaced the frog's legs with brine-soaked paper to detect the flow of electricity
- Developed a device which produced electricity, which could be used to stimulate muscles.
- Volta's Law of Electrochemical Series: "The electromotive force of a galvanic cell is the difference between the electrode potentials"
- Invented the first electric battery.
- The modern term "volt" comes from his name.



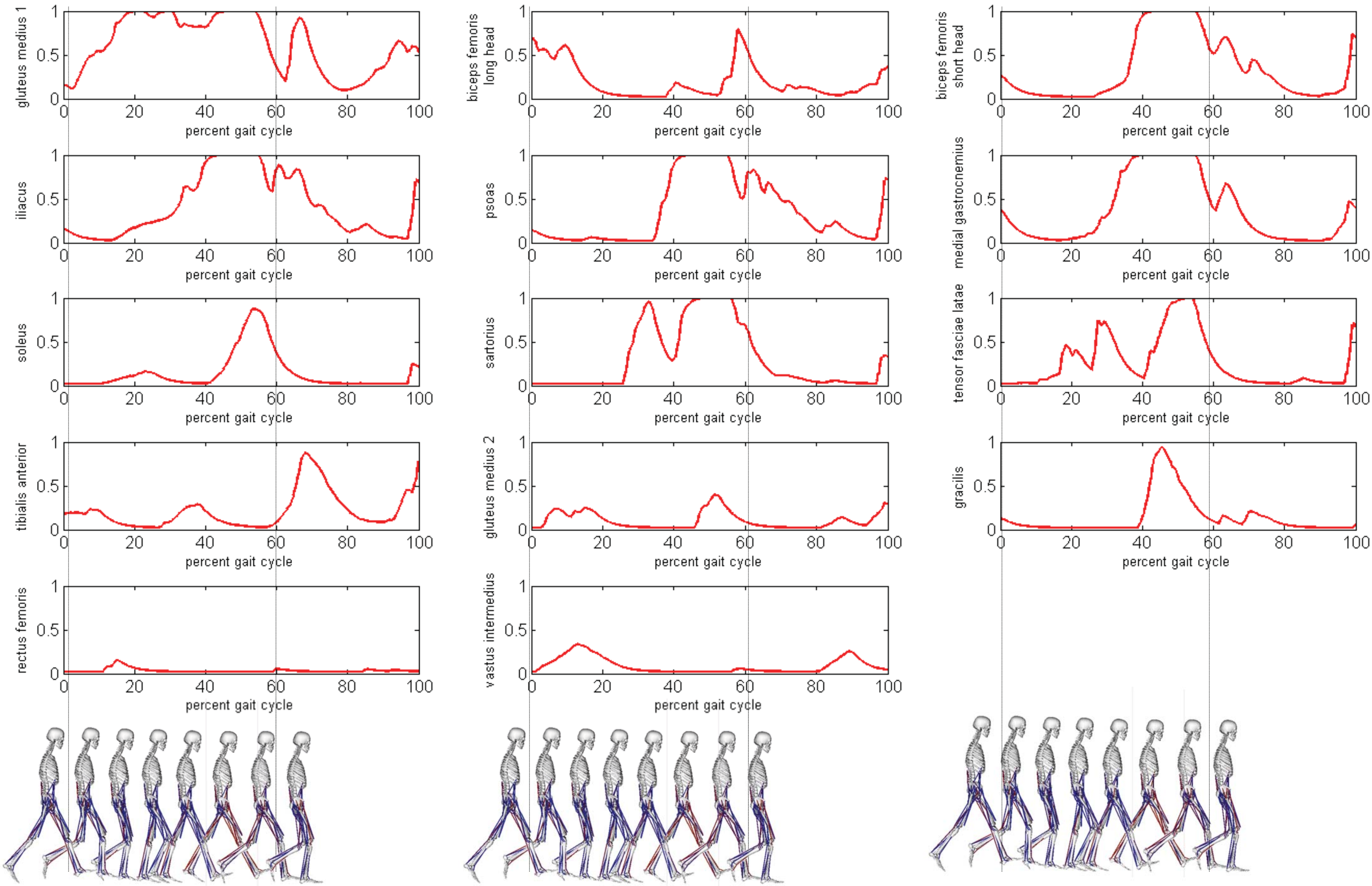
Picture Source: http://www.th.physik.uni-frankfurt.de/~jr/physlist.html and wikipedia

Processed Electromyogram (EMG)

- Raw EMG
- Rectify
- Low-pass filter
- High-pass filter
- Normalize



Muscle Activations during Normal Gait (1.75m/s)

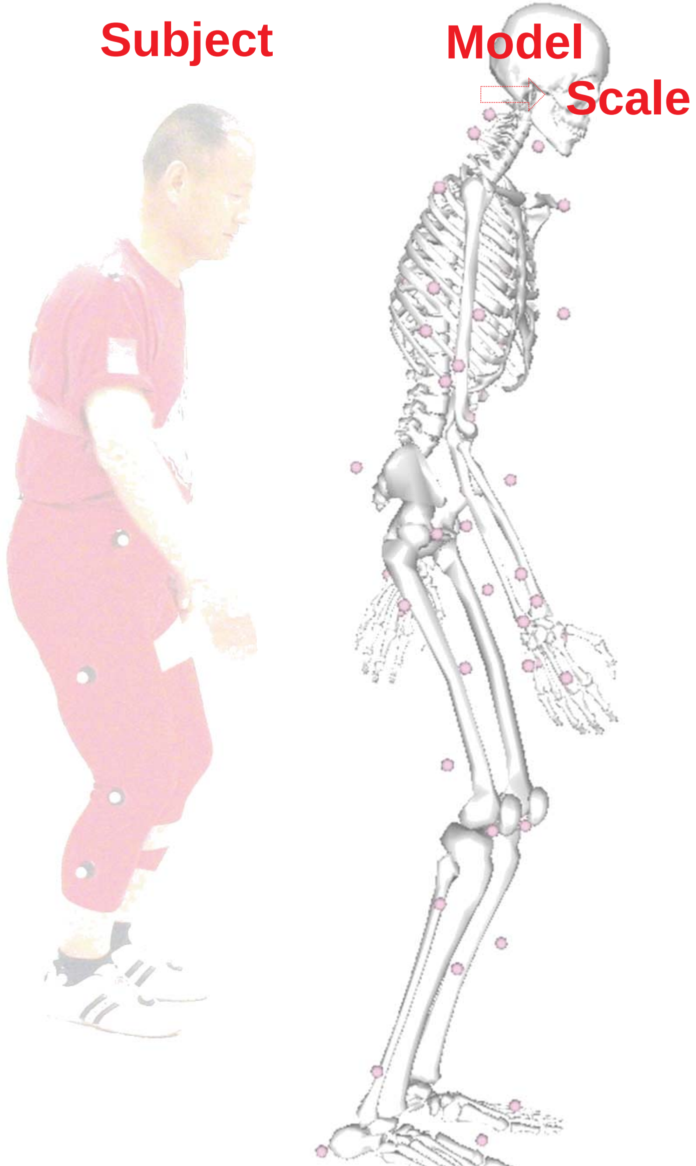


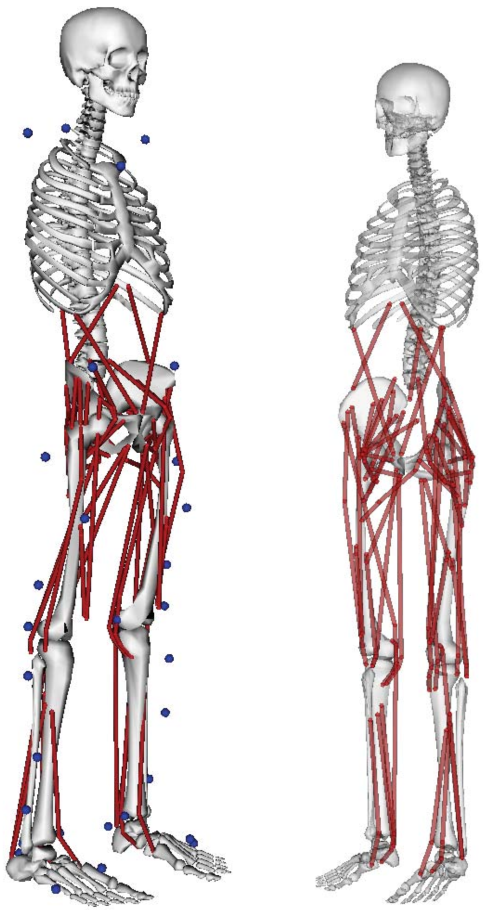
Agenda

- Optometric Methods in Human Motion Analysis
  - Historical Development
  - Basics of Human Gait
  - Non-Optical Methods
  - Optical Methods
  - Related Measurements (Force Plates, EMG)
  - Data Processing, Analysis, and Display
- **Inverse Kinematics and Inverse Dynamics in OpenSim (HW3)**
- Operational Space Formulation
  - Operational Space Dynamics
  - Operational Space Control
  - Human Motion Reconstruction using Operational Space

Mapping Data to Human Model

Scaling





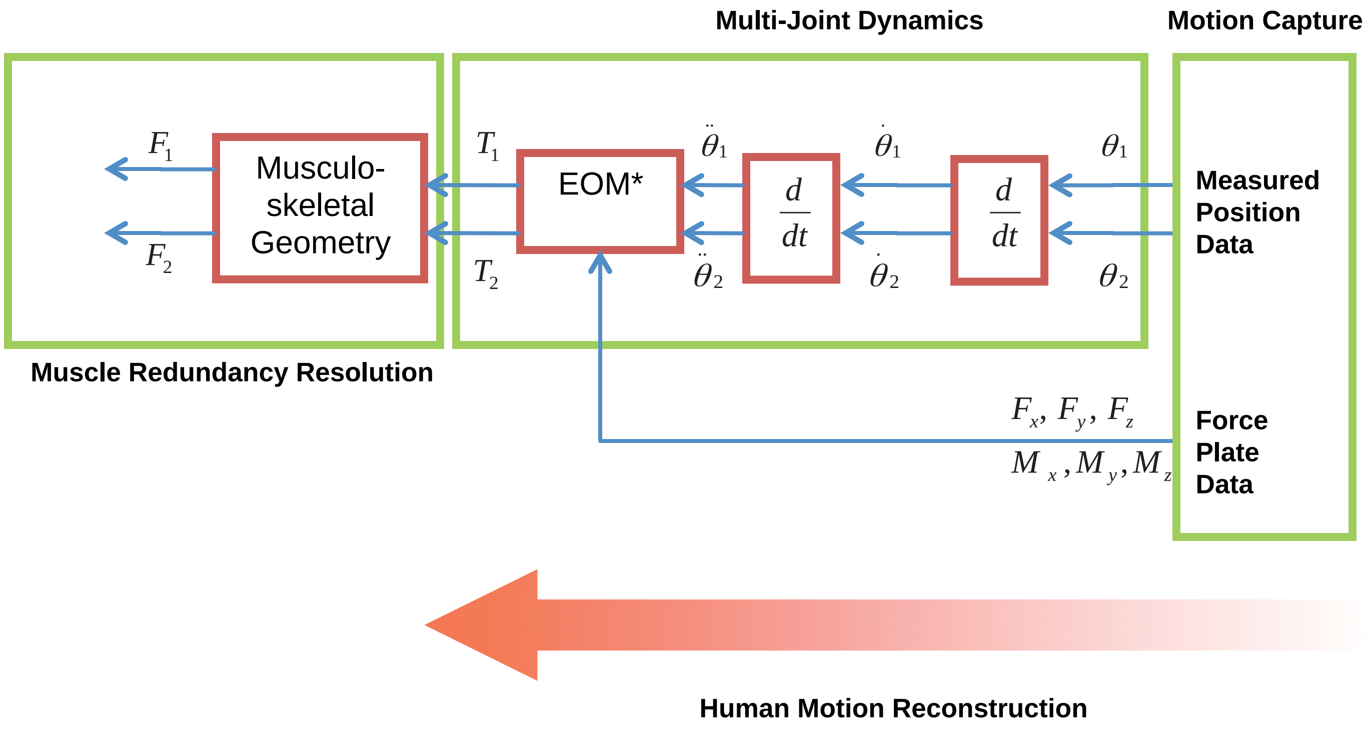
Delp'90
Holzbaur'05

Delp et al'00

Measurement-based scaling

Motion Capture Systems

Human Motion Reconstruction



(Adapted from: Buchanan et al. 2004. Neuromusculoskeletal modeling: estimation of muscle forces and joint moments and movements from measurements of neural command. Journal of Applied Biomechanics)

**: equations of motions*

Agenda

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How to Reconstruct Human Motion?

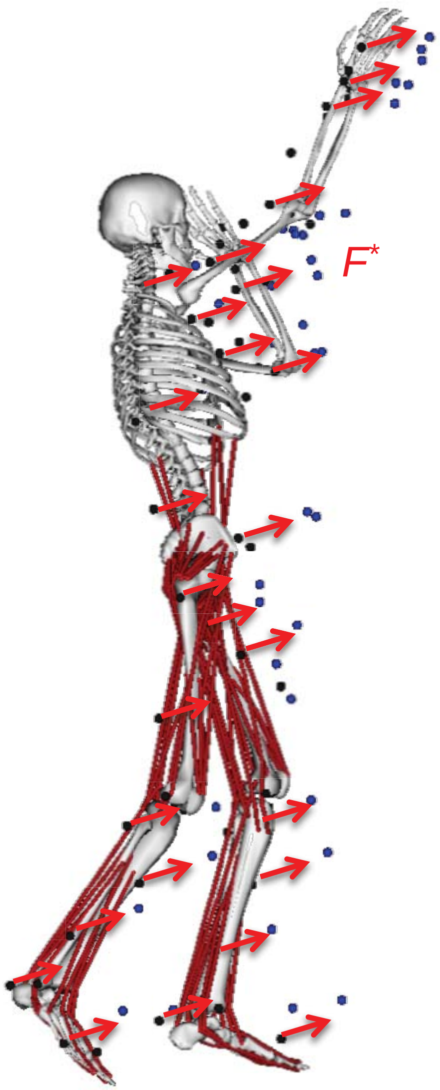
Control and Simulation Framework

Reproducing human movement using robotic algorithms and techniques

- Human are complex articulated body systems
- Robotics brought efficient algorithms and tools for analysis and control
- Redundancy resolution
- Multiple contact and constraints
- Whole-body control, real-time
- Actuation and dynamics characterization tools

Human Motion Reconstruction via Direct Marker Control

Motion Control in Marker Space



$$F^*_{m_i} = \ddot{x}_{m_{i,des}} - k_v(\dot{x}_{m_i} - \dot{x}_{m_{i,des}}) - k_p(x_{m_i} - x_{m_{i,des}})$$

$$F = \Lambda F^* + \mu + p + R$$ (Task Space Dynamics)

Mass Matrix

Centrifugal and Coriolis Forces

Gravity Effect

Contact Forces

Conventional IK techniques are kinematic based

Operational Space Formulation

Task and Posture Decomposition

$$\Gamma = \Gamma_{task} + \Gamma_{posture} = J_t^T F_t + \boxed{N_t^T \Gamma_p}$$

where $$\boxed{\Gamma_{posture} = (J_p N_t)^T F_p = J_{p|t}^T F_{p|t}}$$

$$\Gamma = J_t^T F_t + J_{p|t}^T F_{p|t}$$

For n tasks:

$$\Gamma = J_{t_1}^T F_{t_1} + J_{t_2|t_1}^T F_{t_2|t_1} + \ldots + J_{t_n|t_{n-1}|\ldots|t_1}^T F_{t_n|t_{n-1}|\ldots|t_1}$$

Constraint-Consistent Task Space Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

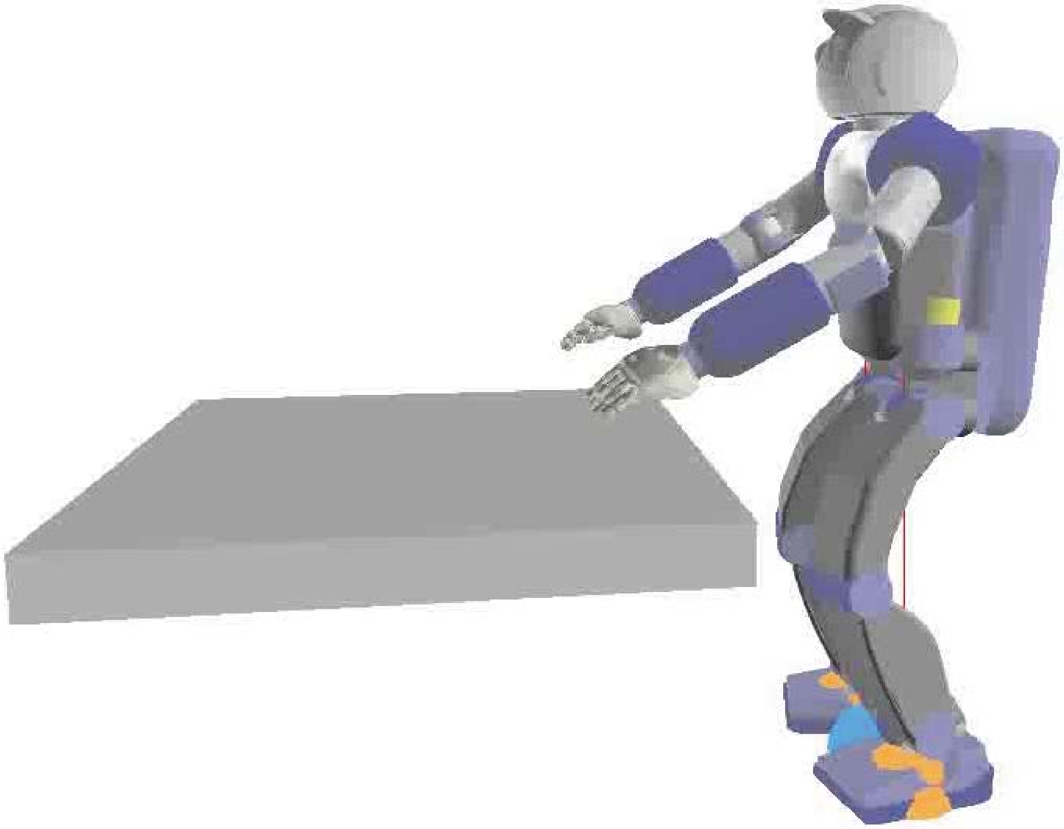
Balance

Internal Constraints
Self Collision
Local Obstacles

Contact

Task

Posture



Whole-body Control of Marker Task

Tracking the Actual Markers of Human Movement

$$\Gamma = \Gamma_{m_1} + \Gamma_{m_2} = J_{m_1}^T F_{m_1} + \boxed{N_{m_1}^T \Gamma_{m_2}}$$

where $\boxed{\Gamma_{m_2} = (J_{m_2} N_{m_1})^T F_{m_2} = J_{m_2|m_1}^T F_{m_2|m_1}}$

$$\Gamma = J_{m_1}^T F_{m_1} + J_{m_2|m_1}^T F_{m_2|m_1}$$

For n marker tasks:

$$\Gamma = J_{m_1}^T F_{m_1} + J_{m_2|m_1}^T F_{m_2|m_1} + \ldots + J_{m_n|m_{n-1}|\ldots|m_1}^T F_{m_n|m_{n-1}|\ldots|m_1}$$

Task Space Control Framework

Prioritized Control of Marker Tasks

Marker Task 1

Marker Task 2

...

Marker Task n

$$\Gamma = J_{m_1}^T F_{m_1} + J_{m_2|m_1}^T F_{m_2|m_1} + \ldots + J_{m_n|m_{n-1}|\ldots|m_1}^T F_{m_n|m_{n-1}|\ldots|m_1}$$

Constraint-Consistent Task Space Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

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Self Collision
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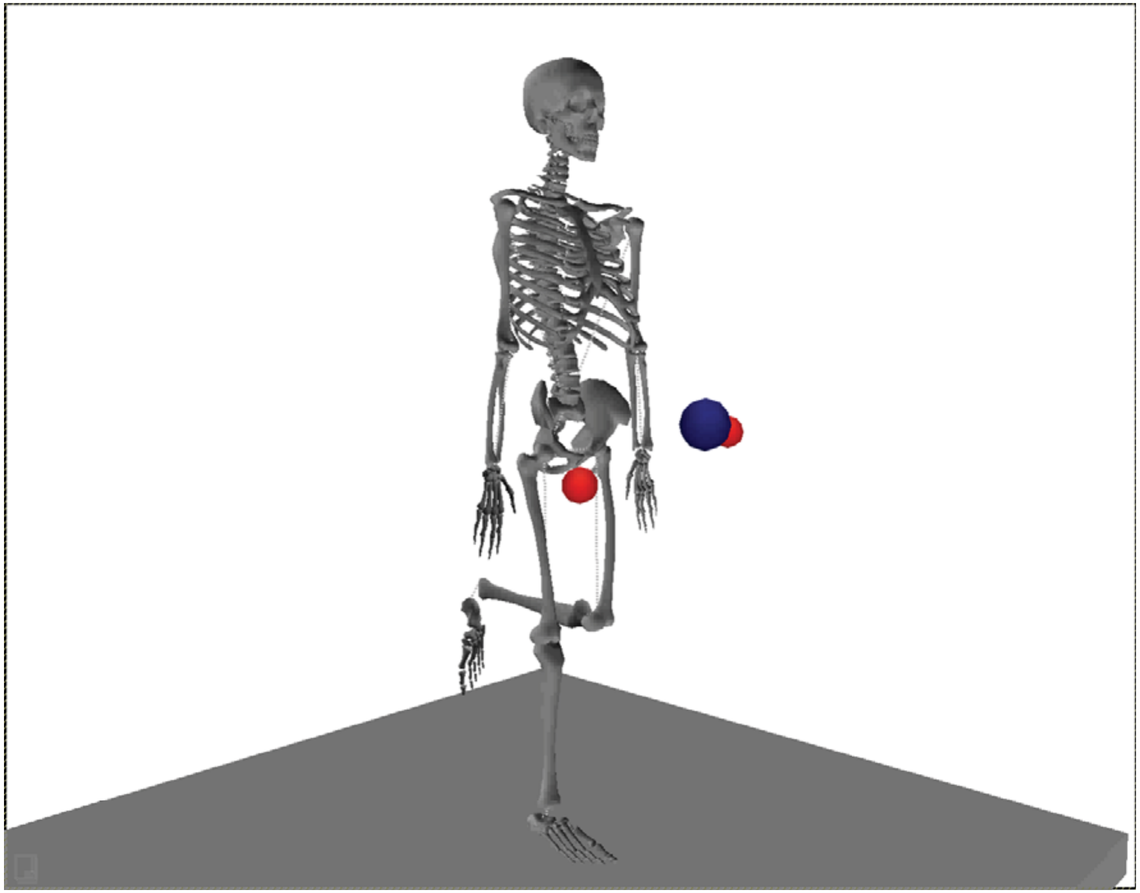
Posture



Constraint-Consistent Task Space Framework

Task, Posture, Constraints, Multiple Contacts, and Balance

Constraints:

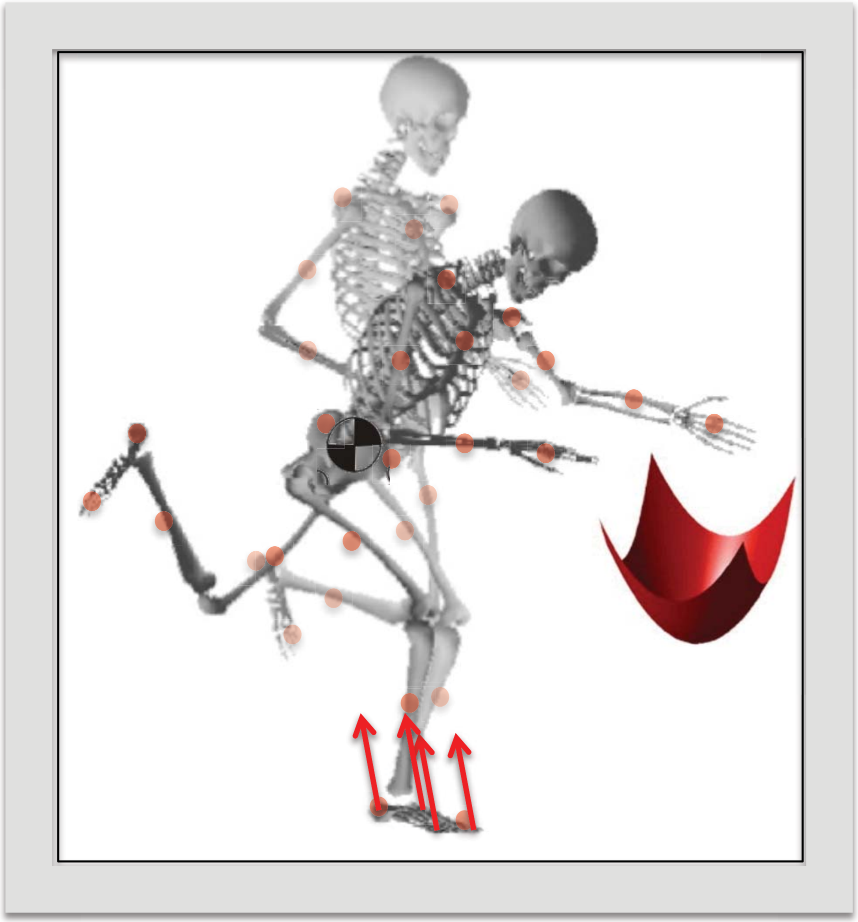
- Contact
- Joint limits
- Collision Avoidance
- Balance

Marker Tasks:

- Marker Task 1
- Marker Task 2
- …
- Marker Task n

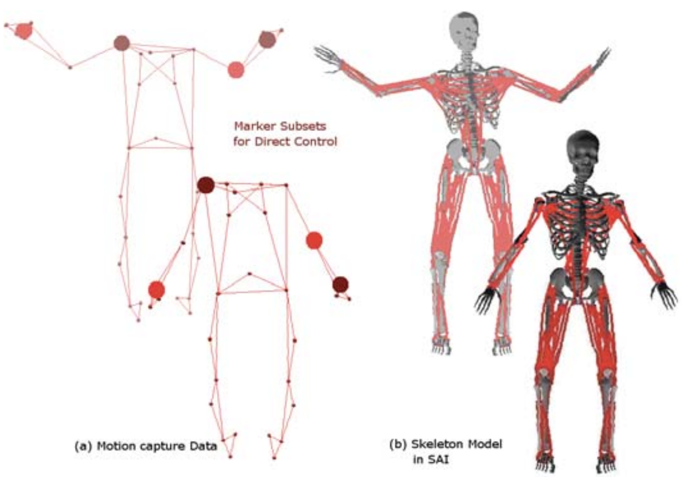
Posture:

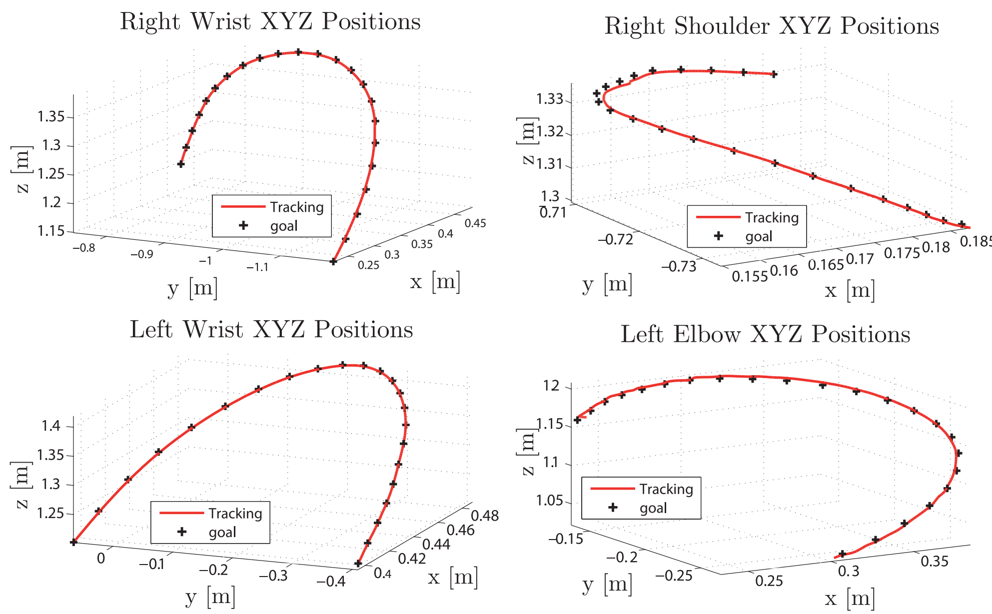
- Body Symmetry
- Body Orientation
- Effort Minimization



Experiment – Tai Chi Motion Sequence

Level 1	Level 2	Level 3	Level 4
Balance	Rshoulder	Rwrist	*Posture*
	Lwrist	Lelbow	

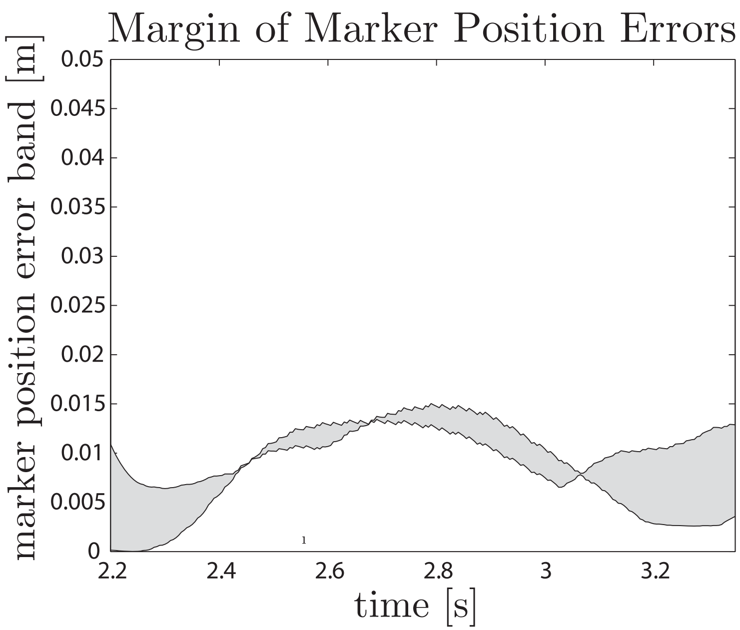


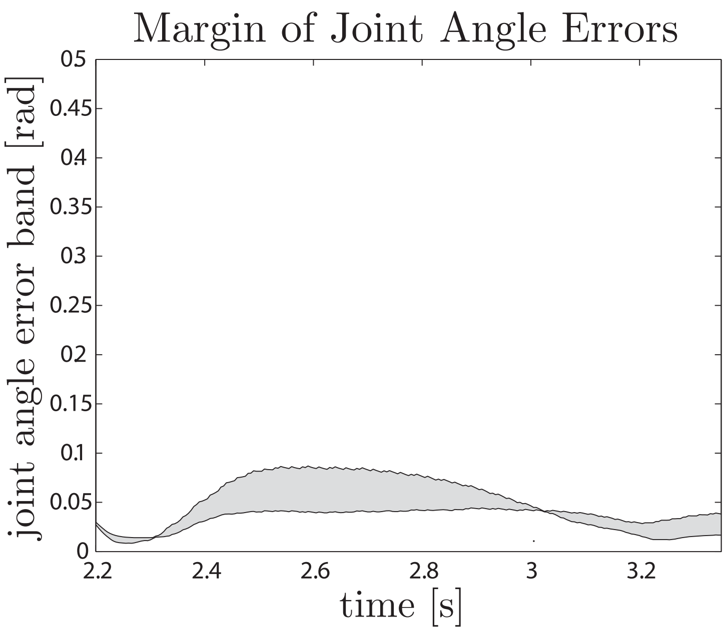


- Average error in position: 0.005m
- Average error in joint angle: 2.8° ≈ 0.05rad

Demircan, E., Sentis, L., DeSapio, V., and Khatib, O., "Human Motion Reconstruction by Direct Control of Marker Trajectories", Advances in Robot Kinematics, Springer, 11th International Symposium, Batz-sur-Mer, France, June 2008.

Margin of Errors over the Trajectory





$$\Delta x_{\otimes} = J_{\otimes} \Delta q$$

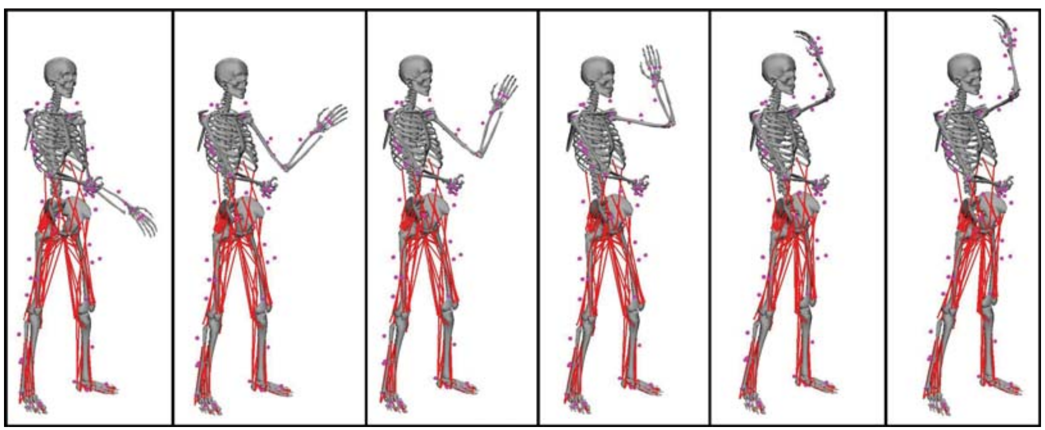
$$|\Delta q| \leq |\bar{J}_{\otimes}||\Delta x_{\otimes}|$$

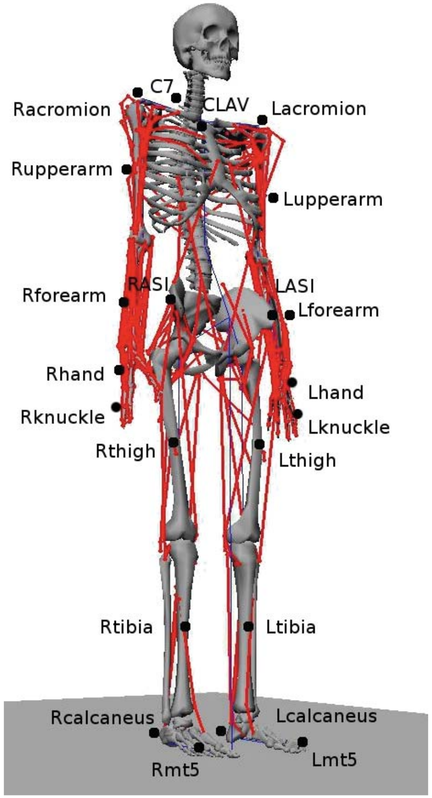
- Joint angle error magnitudes show a stable variation over the trajectory, ensuring well bounded errors on the joint angles.

Experiment – Throwing

Whole-Body Motion Reconstruction with Human Musculoskeletal Model

Level 1	Level 2	Level 3	Level 4
Pelvis	Torso	Lupperarm	*Posture*
Lhand	Lthigh	Rupperarm	*Additional Behaviors*
Rhand	Rthigh	Ltibia	
Lmt5	Lforearm	Rtibia	
Rmt5	Rforearm		
Lknuckle	Lcalcaneus		
Rknuckle	Rcalcaneus		



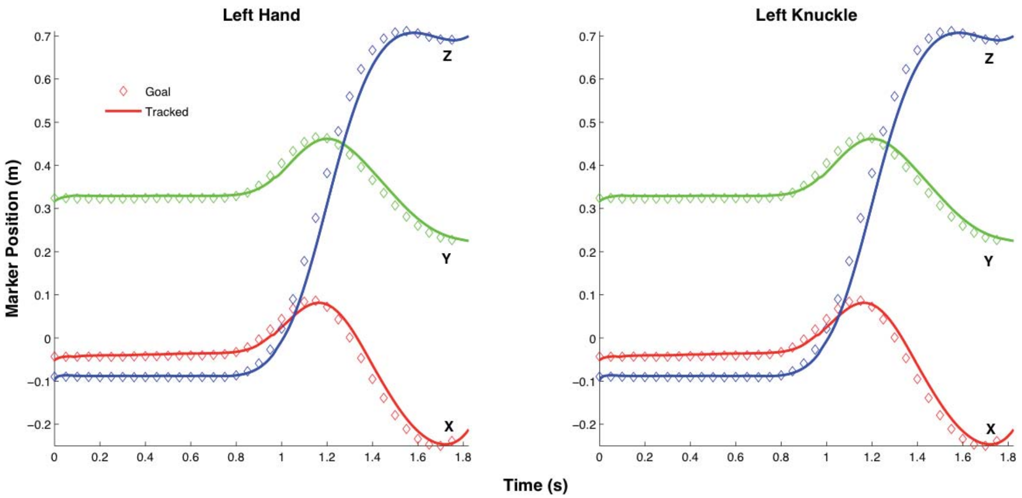


- Tasks in three-level marker space
- Sets of 22 experimental marker trajectories

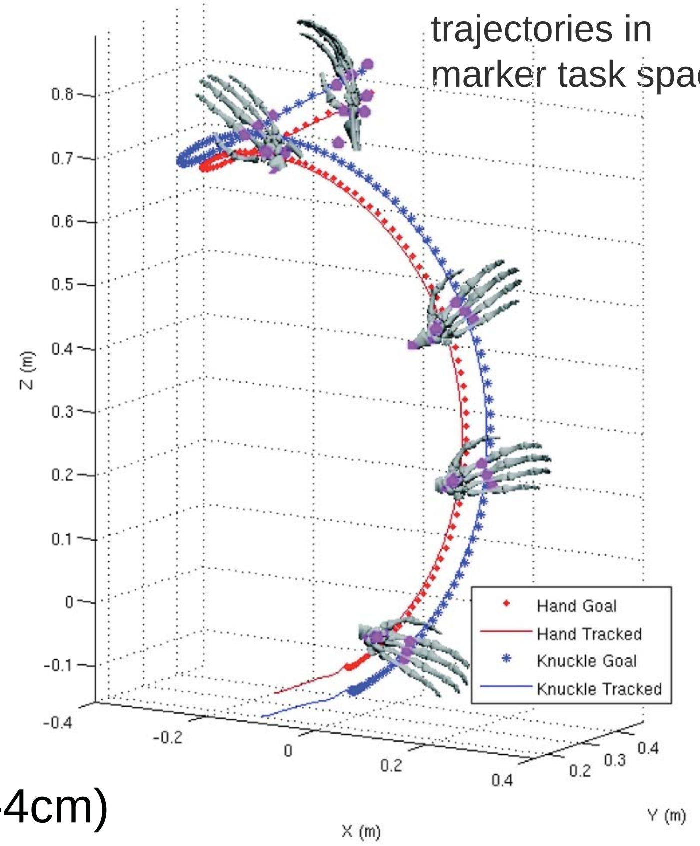
Demircan, E., Besier, T., Menon, S., and Khatib, O., “Human Motion Reconstruction and Synthesis of Human Skills”, Advances in Robot Kinematics, Springer, 12th International Symposium, Piran-Portoroz, Slovenia, June 2010

Experiment – Throwing

Tracking Results



Hand marker trajectories in marker task space



- Tracking the trajectories with little error (0-4cm)
- Principal error source: scapular elevation and depression of the shoulder

Today

- Motion Tracking Techniques
- Introduction to OpenSim Scaling, IK, ID
- Introduction to Operational Space Formulation and Human Motion Reconstruction

Schedule

4/18: Introduction
4/25: Spatial Descriptions, Kinematics, Introduction to Biomechanical Simulation
5/2: Skeletal Muscle Structure, Force Generation, Musculoskeletal Geometry
5/9: Production of Movement
5/23: Motion Tracking Techniques
6/27: **Inverse Dynamics, Control, Operational Space Formulation**
6/27: Human Articulated Body Model, Dynamics, and Motion Control
7/4: Advanced Topics in Human Motion Analysis, Student Presentations

6/6: ICRA'14 (no lecture), HW 3 is out (via email)
6/27: Lecture & HW 3 due

Thank you!

Mechanical Engineering Seminar (U-Grad)
Special Topics in Mechano-Informatics II (Grad)
"Biomechanics of Human Movement"

May 23rd, 2014

Dr. Emel Demircan