Humanoids 2008
Workshop on Imitation and Coaching in Humanoid Robots

Kinematic and Dynamic Adaptation of Human Motion for Imitation

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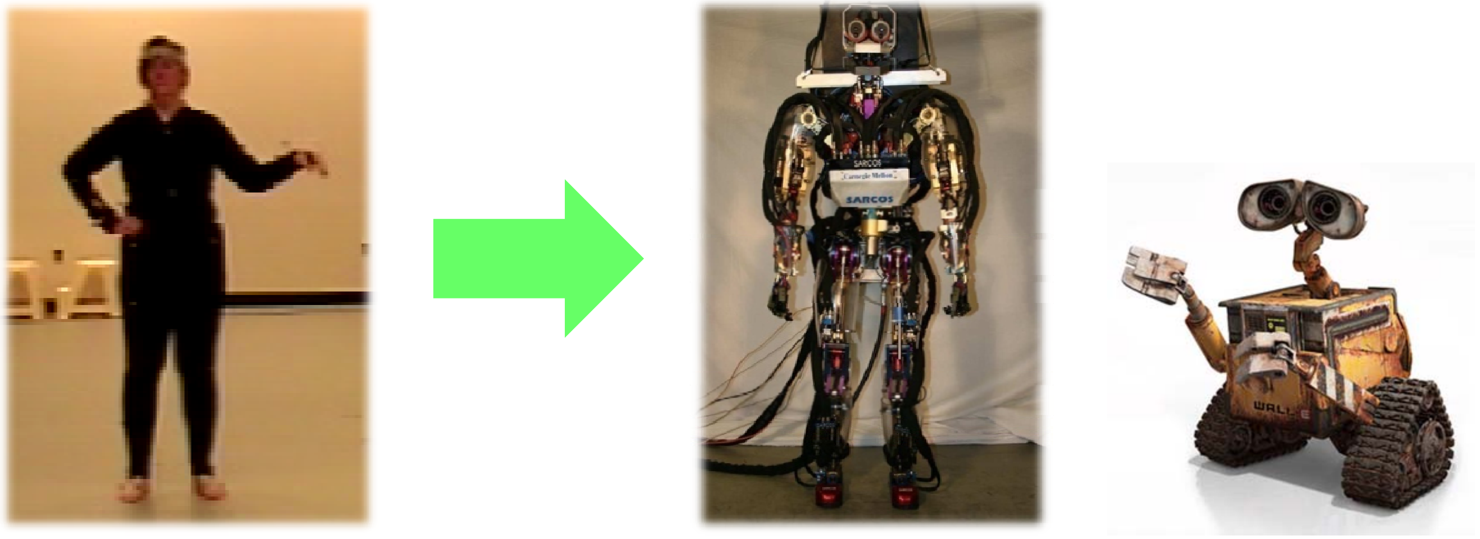
Programming Robots through Imitation

- needs to adapt observed human motions to
  - robot kinematics / dynamics
    - different limb length, mass, actuation, …
  - new environment / constraints
    - collision avoidance, task, …



Issues

- different kinematics / dynamics
  - may be physically infeasible
  - may not be able to accomplish the task
- what can be modified / what has to be preserved
  - joint trajectory, endeffector trajectory, contact force, …
  - usually task-dependent
- human adaptation
  - acquired by practice
  - once acquired, easily adapted to various scenes
  - sophisticated motor control? memory?

Related Work

- common problem in robotics and graphics
  - usually formulated as an optimization problem
- synthesis
  - mathematical optimization [Gleicher et al. 1997] [Ude et al. 2004] [Liu et al. 2005]
  - learning [Kuniyoshi et al. 1994] [Atkeson, Schaal 1997] [Bentivegna et al. 2004]
  - task sequence [Nakaoka et al. 2007]
- analysis
  - motion graphs [Kovar et al. 2002] [Lee et al. 2002]
  - motor control [Mataric 2002]

Talk Overview

1. adaptation techniques

	kinematics	**dynamics**
1) dynamics filter [Yamane, Nakamura 2003]	slightly different	
2) synthesizing manipulation tasks [Yamane, Kuffner, Hodgins 2004]	very different environments and characters	(quasi-static)
3) motorized marionette [Yamane, Hodings, Brown 2003]	limited mobility	different actuation mechanism

2. understanding human adaptation

detailed neuro-musculoskeletal human model

[Yamane et al. 2005] [Murai et al. 2008]

Adaptation Techniques

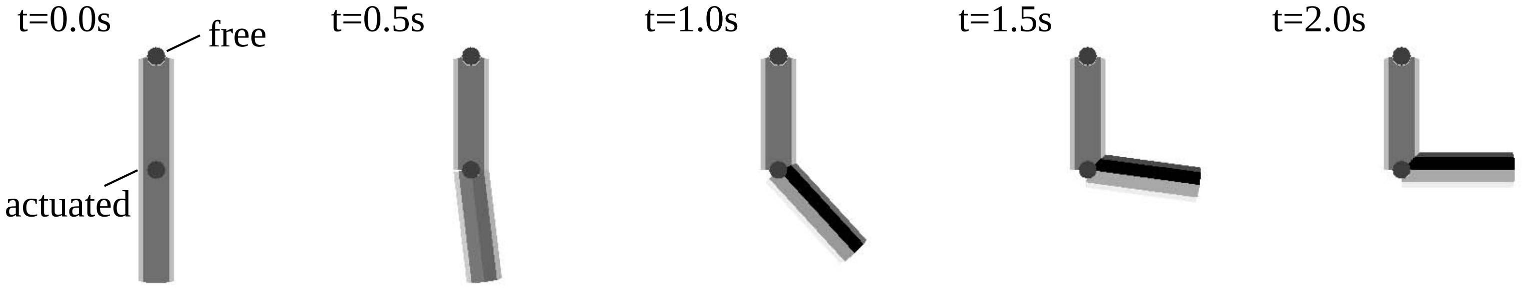
1. Dynamics Filter

[Yamane and Nakamura 2003]

Dynamics Filter

- convert a physically infeasible motion to a feasible one
- simple example

original



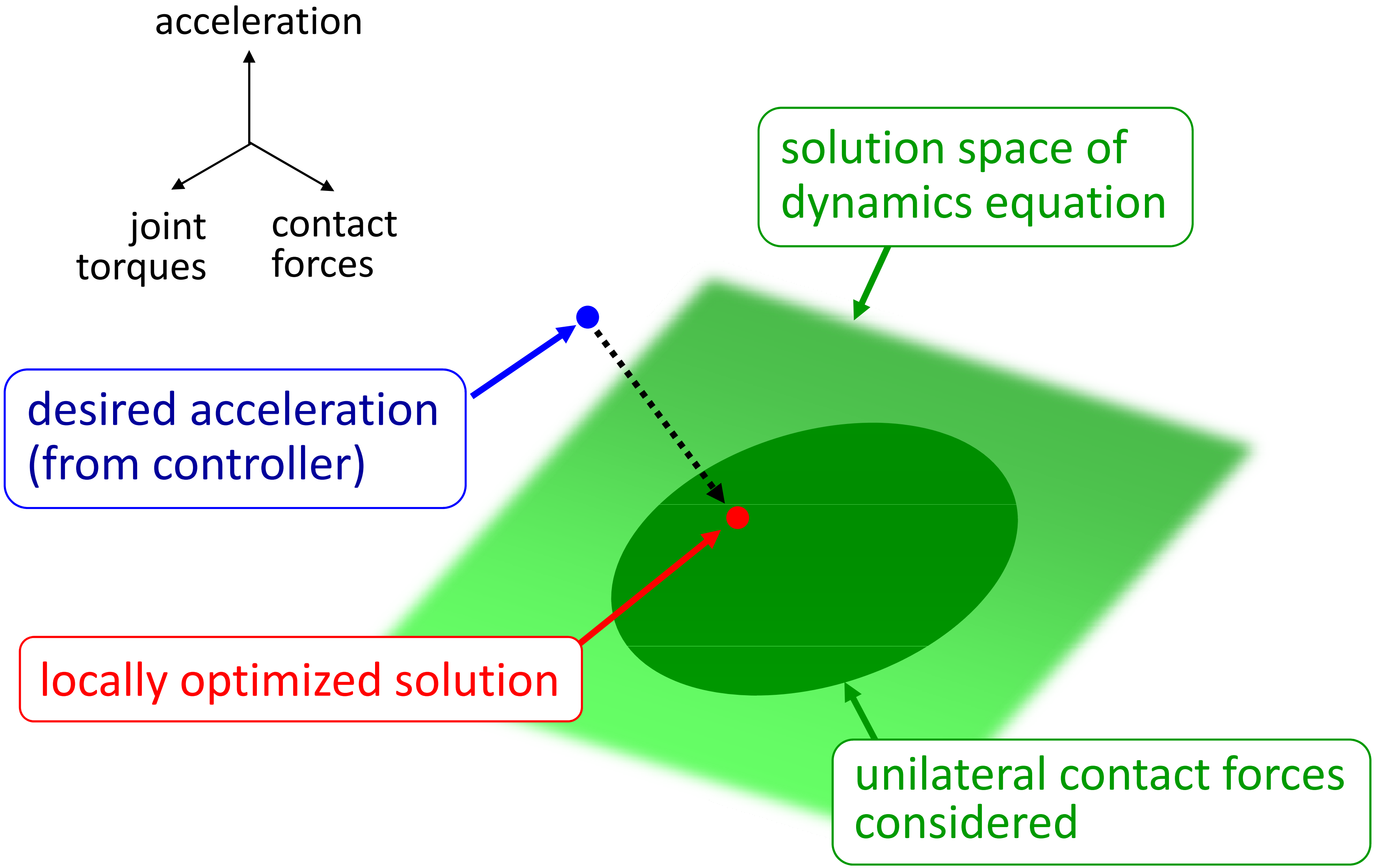
converted

Dynamics Filter

- convert a physically infeasible motion to a feasible one
  - reasons for infeasibility
    - measurement error
    - different kinematic/dynamic parameters
    - manual editing

- technique
  - obtain desired accelerations by a feedback controller in joint/Cartesian spaces
  - project the accelerations onto feasible space by local (online) optimization
  - limitation: can only cope with small differences

Dynamics Filter: Concept



acceleration

joint torques

contact forces

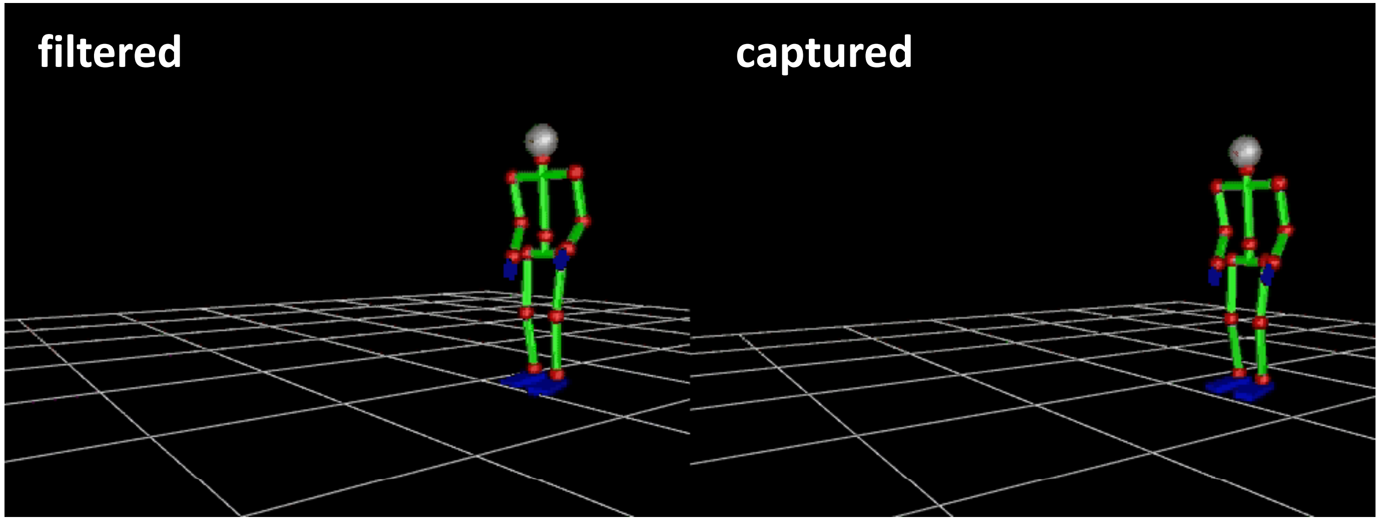
solution space of dynamics equation

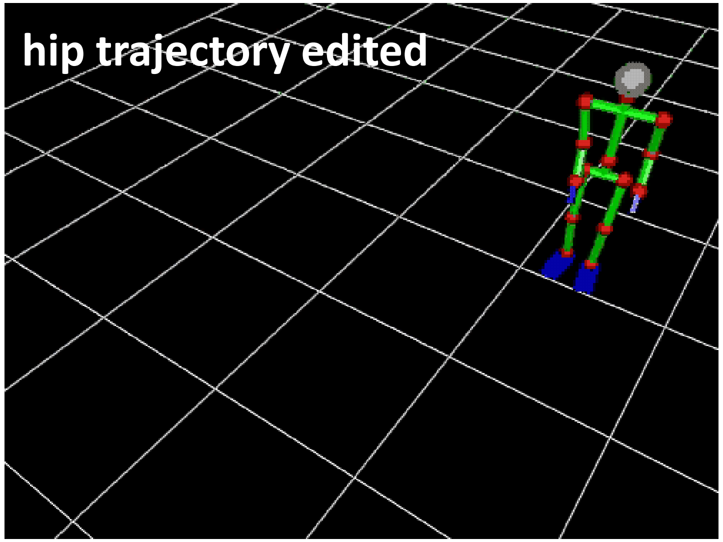
desired acceleration (from controller)

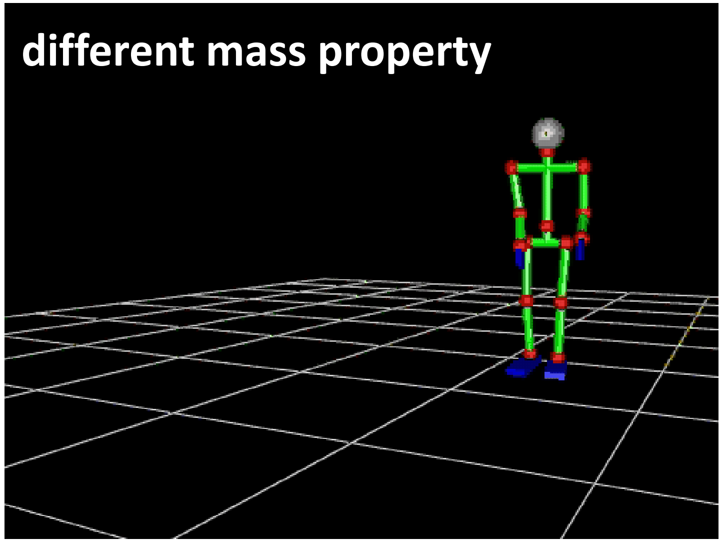
locally optimized solution

unilateral contact forces considered

Dynamics Filter: Examples







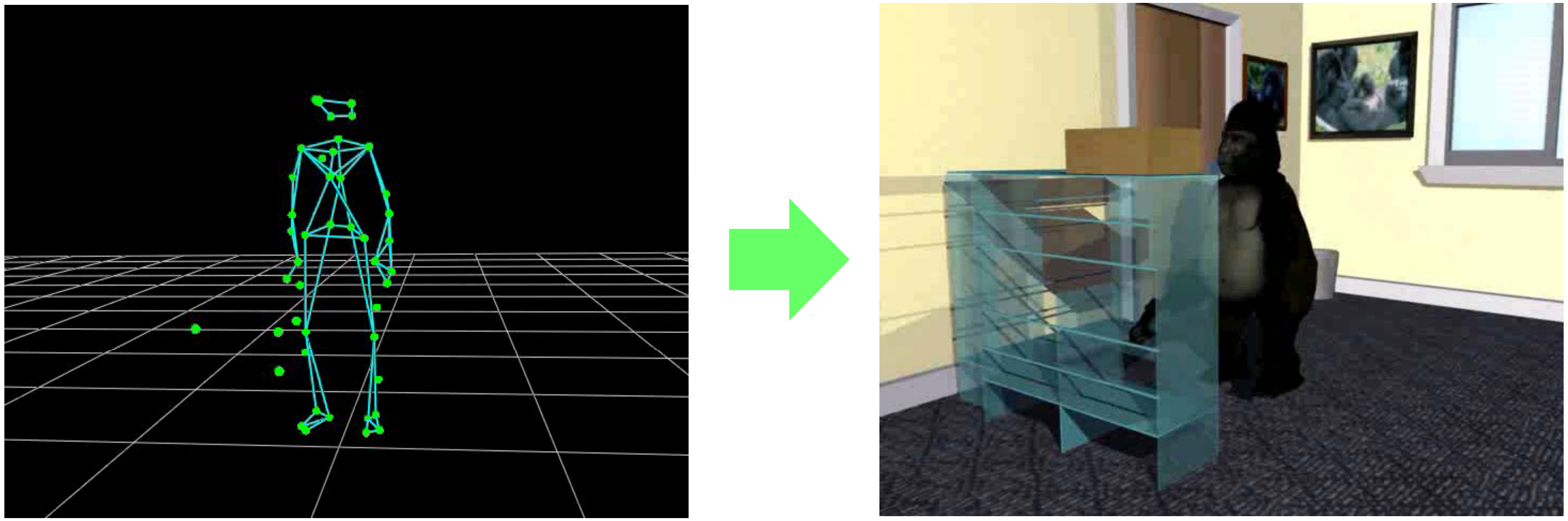
Adaptation Techniques

2. Synthesizing Manipulation Tasks

[Yamane, Kuffner, Hodgins 2004]

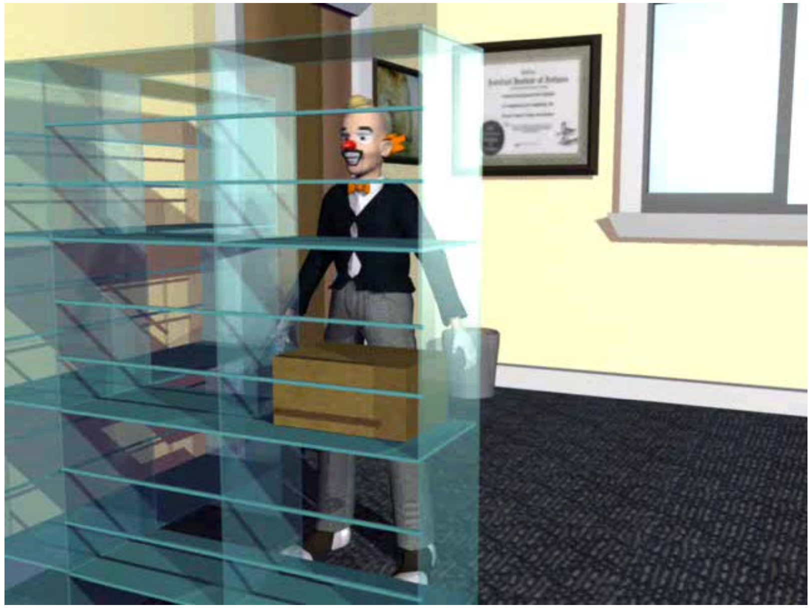
Synthesizing Manipulation Tasks

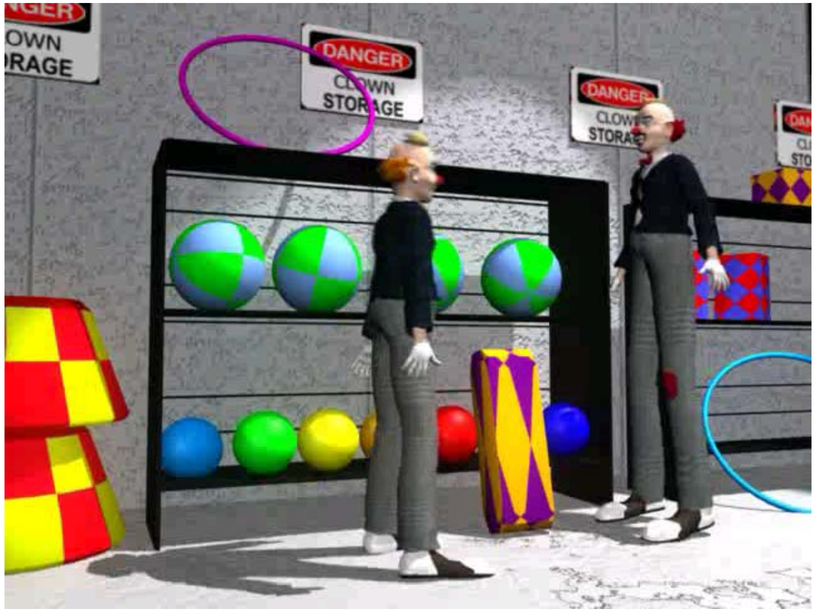
- adapt example motions to
    - new objects
    - new environment
    - new task (start/goal positions)



Synthesizing Manipulation Tasks

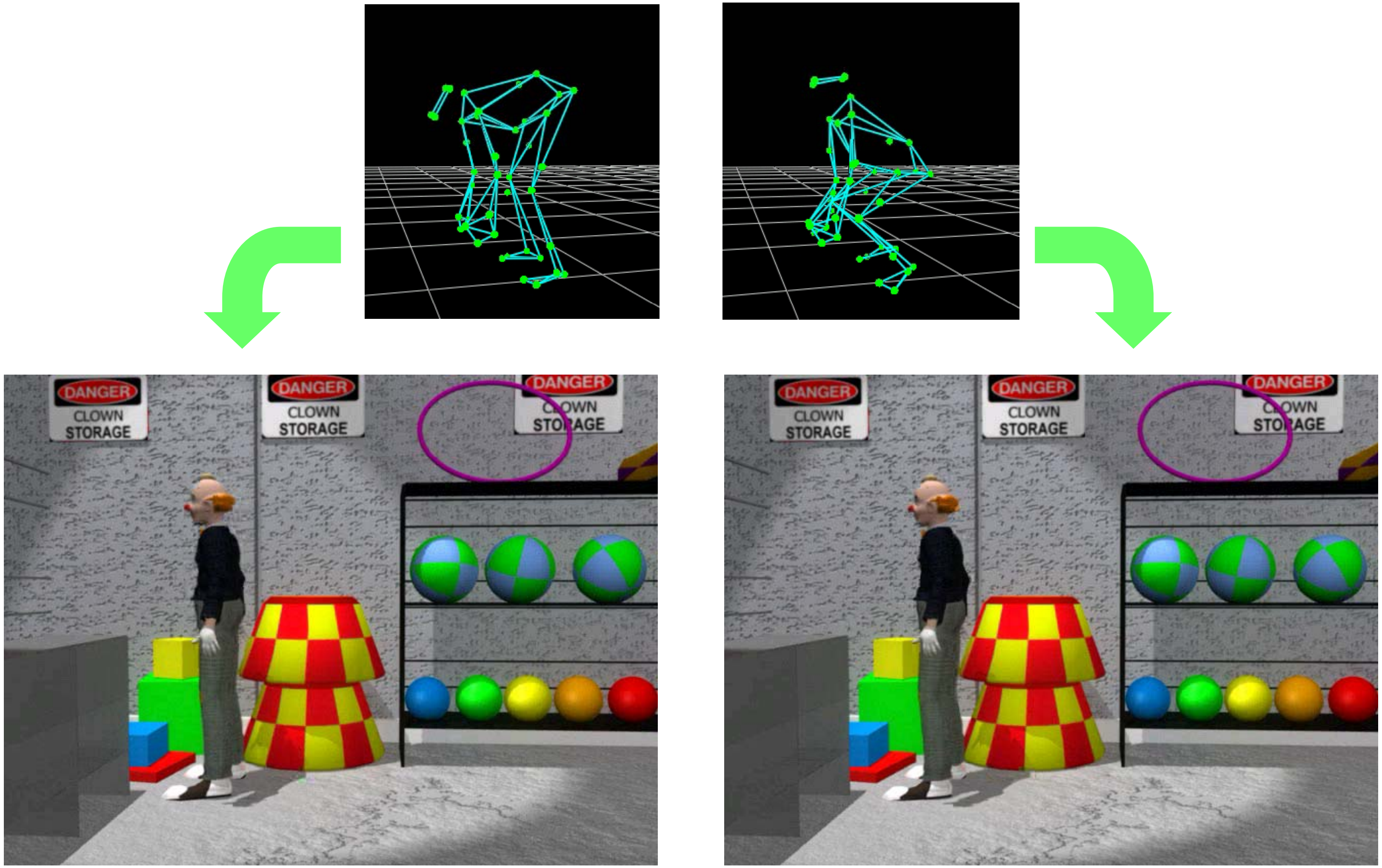
- combination of model and data
  - motion planning (RRT) [LaValle and Kuffner 2000] and inverse kinematics (UTPoser) [Yamane and Nakamura 2003]
  - relatively small data set (four pick-and-place examples)
- results





Synthesizing Manipulation Tasks

- using motion capture to bias IK



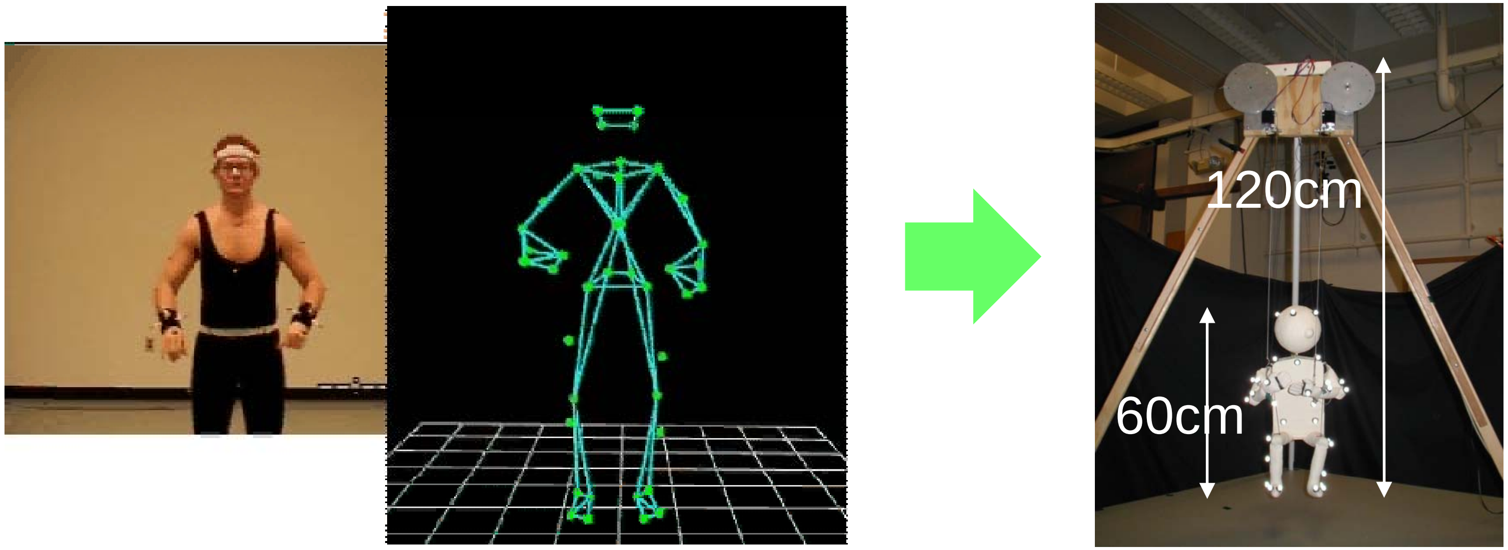
Adaptation Techniques

3. Motorized Marionette

[Yamane, Hodgins, Brown 2003]

Motorized Marionette

- programming marionettes by imitation
  - inexpensive device for entertainment



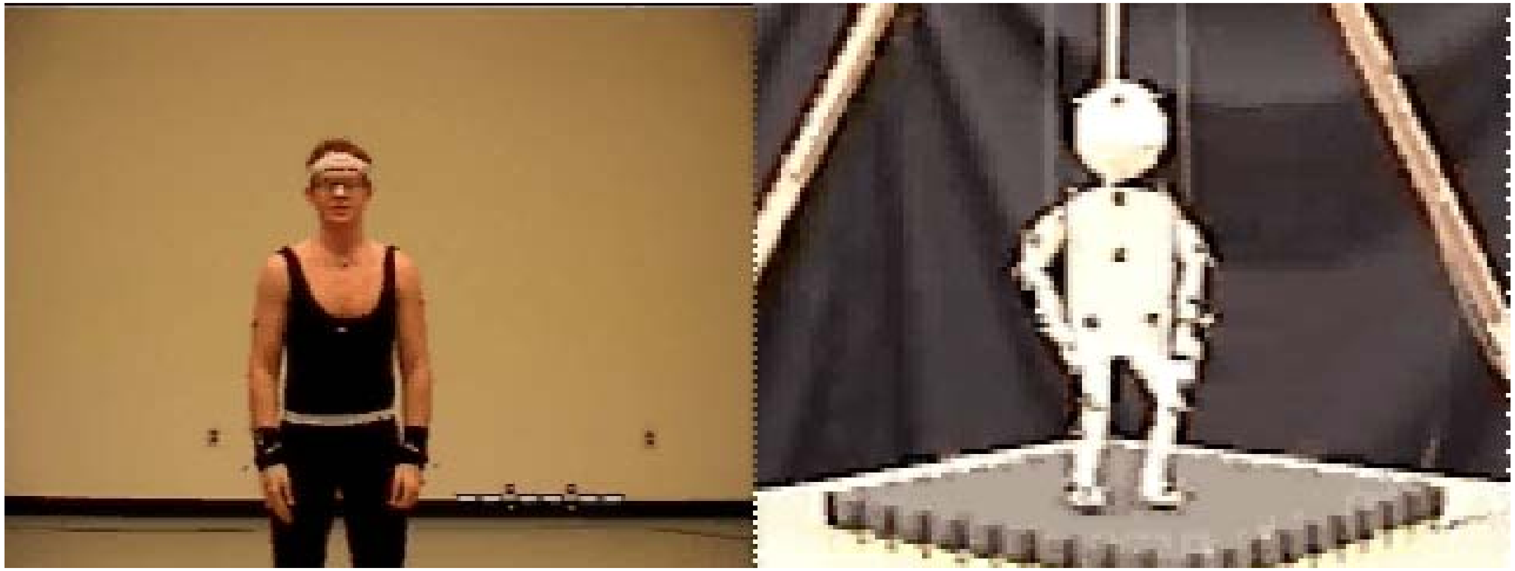
- issues
  - different actuation mechanism
  - very limited mobility

Motorized Marionette

- issues and solutions
  - mapping marker data to marionette’s motion range

    →inverse kinematics with string length/direction constraints
  - undesired swing

    →linear string model and feedforward swing suppression controller



Understanding Human Adaptation

Neuro-Musculoskeletal Human Model

Human Adaptation

- when human learns from observation
  - understands the demonstrator’s intention
  - acquires the motion through learning (practice)
  - once acquired, instantly adapted to new environments, constraints and disturbances

- questions
  - how do we understand the demonstrator’s intention?
  - what is the mechanism to realize instant adaptation?

Understanding Demonstrator’s Intention

- what has to be preserved?
  - joint trajectory
  - endeffector trajectory
  - external force
  - compliance
  - something else?

- automatic extraction is an open issue
  - observing joint trajectories is not enough (obviously)
  - analyzing multimodal data is essential

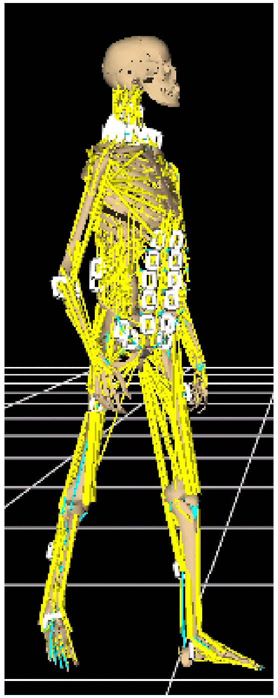
Instant Adaptation

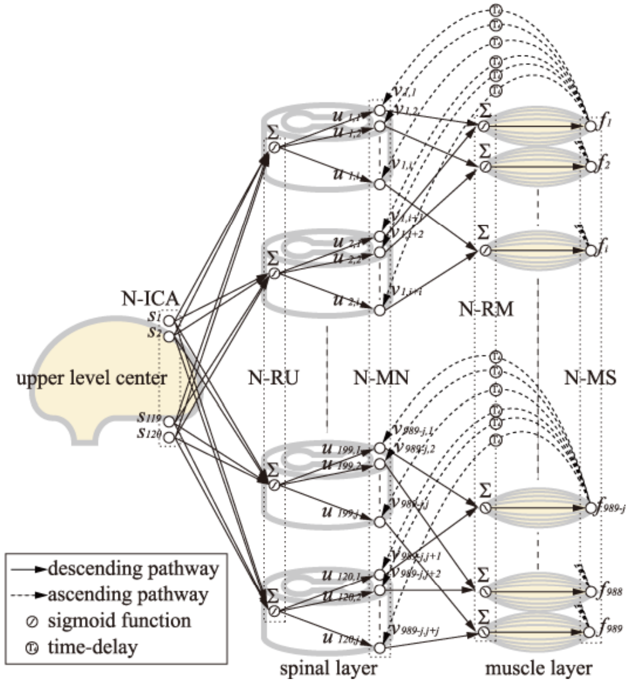
- hierarchy of controllers
  - high-level motor control in the brain
    - large (100ms+) delay: too slow to cope with disturbance?
  - low-level reflex in the spinal cord
    - sensors
      - somatosensory information (muscle length, tension)
      - touch, temperature, pain
    - smaller (~30ms) delay
    - most humanoid controllers run at or faster than 1KHz

      → sophisticated mechanism should exist

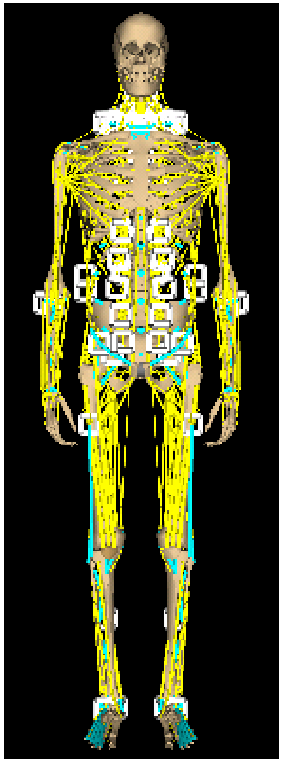
Towards Human-Level Adaptation

- models for analysis
  - detailed musculoskeletal model for estimating the somatosensory information [Yamane et al. 2005]
  - neuromuscular network model with somatosensory reflex [Murai et al. 2008]





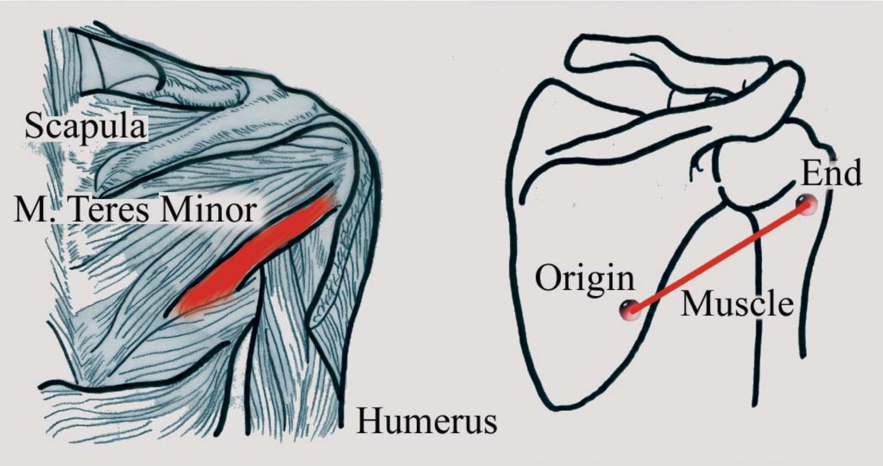
Musculoskeletal Model

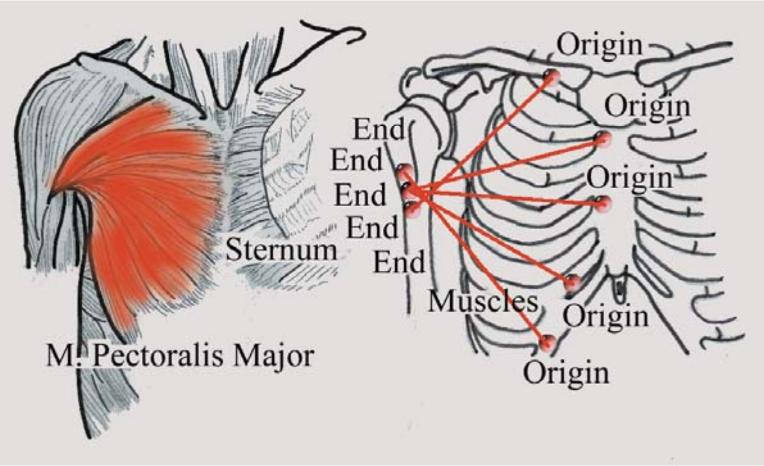


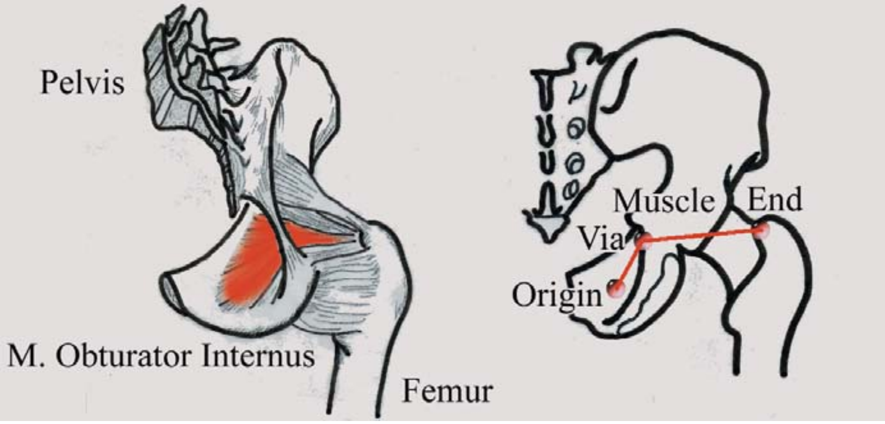
- skeleton: 155 DOF
  - 200 bones → 53 groups
  - composed of mechanical joints
  - hand/foot fingers not included
- actuator: more than 1,000 wires
  - 997 muscles: linear actuators
  - 50 tendons: connect muscles and bones
  - 117 ligaments: constrain the bones
- algorithms
  - inverse kinematics → muscle length / velocity
  - inverse dynamics → muscle tension estimation

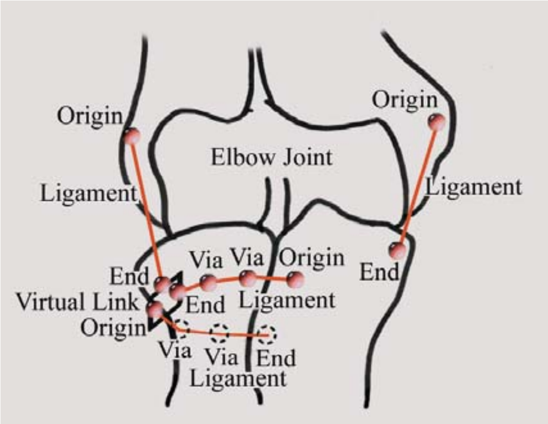
Musculo-Tendon Network

- mass-less, zero-radius wires with via-points



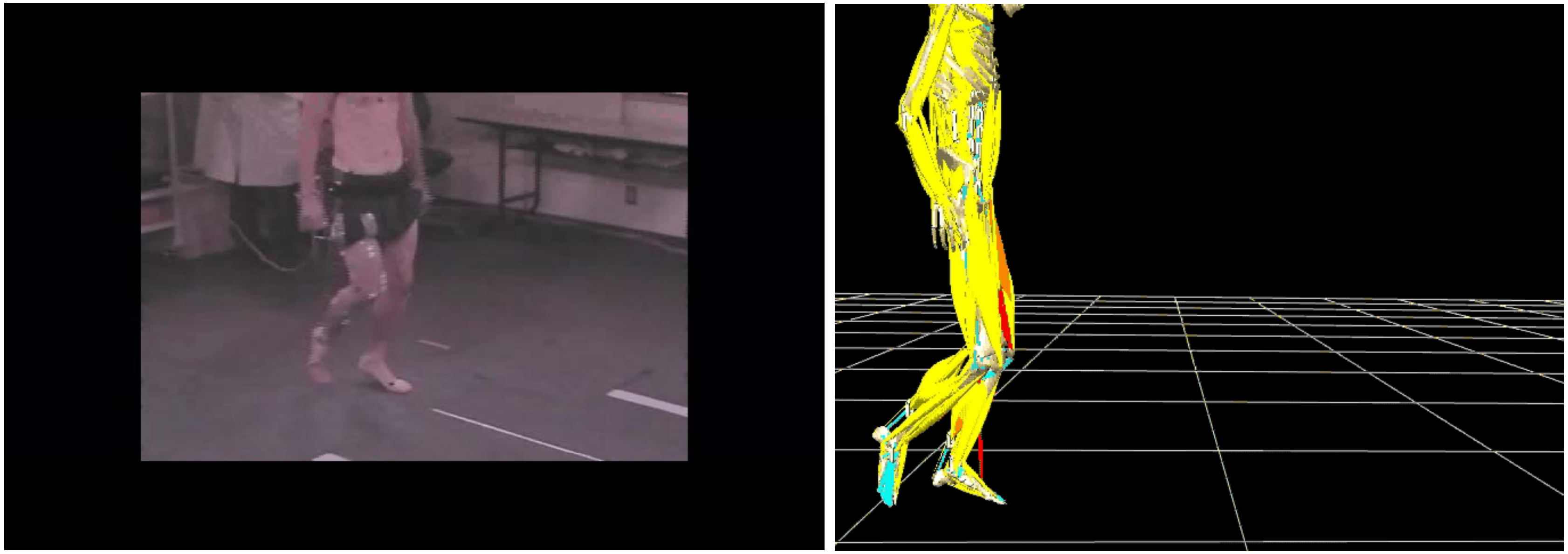




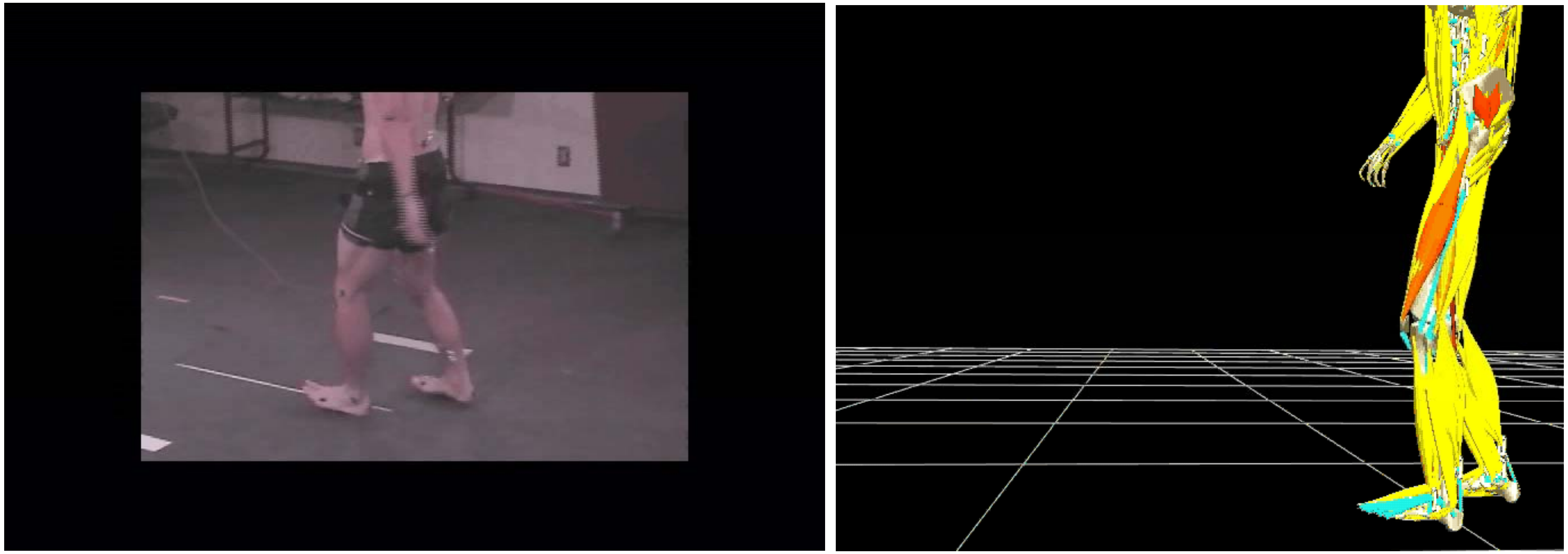


Example: Muscle Tension Estimation

toe
walk

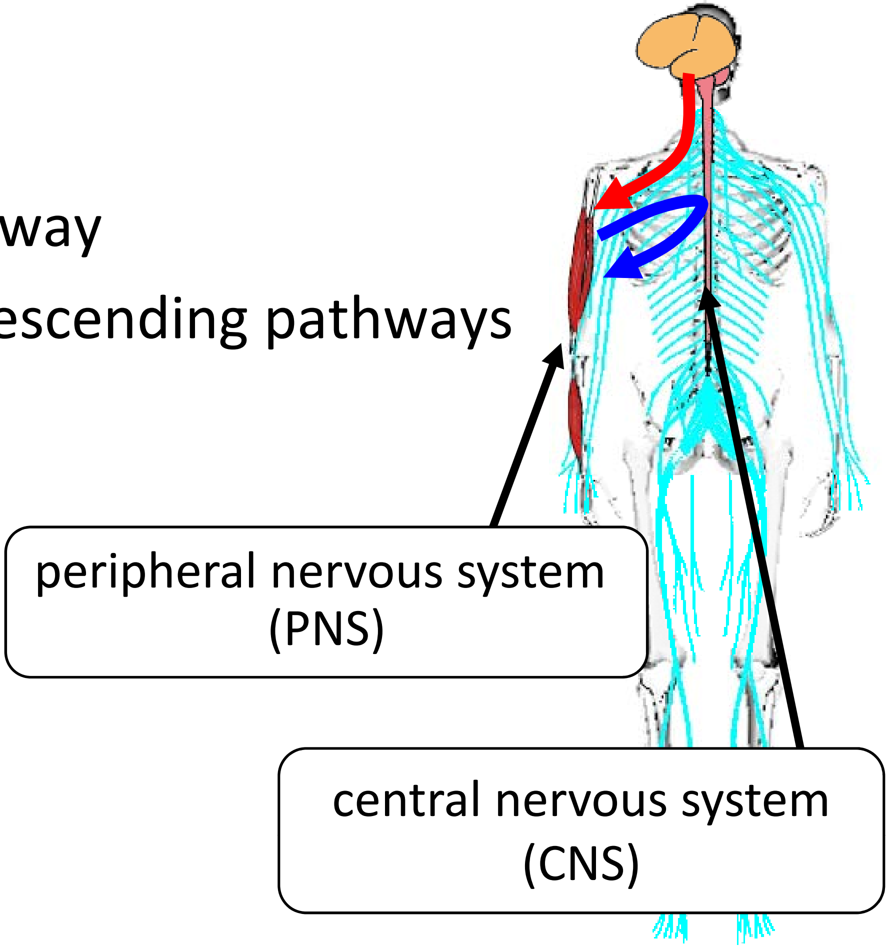


heel
walk



Neuromuscular Network Model

- input and output of the model
  - input: motor command signals at spinal nerve rami
  - output: muscle tension
- two paths:
  - CNS→PNS: descending pathway
  - PNS→PNS: ascending and descending pathways (somatic reflex network)



peripheral nervous system (PNS)

central nervous system (CNS)

Identifying the Motor Command Signals

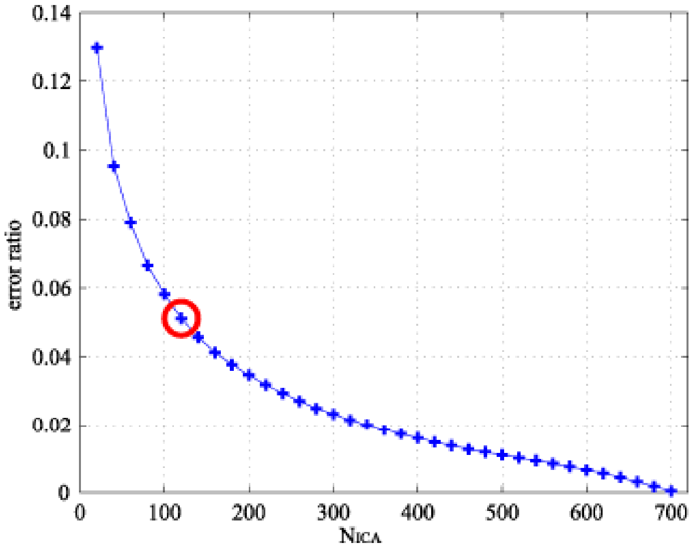
- independent component analysis (ICA)
  - estimate mutually independent signal sources
  - order of the independent signals is undefined

$$\mathbf{f} = \mathbf{W}_{\mathrm{ICA}}\mathbf{s}$$

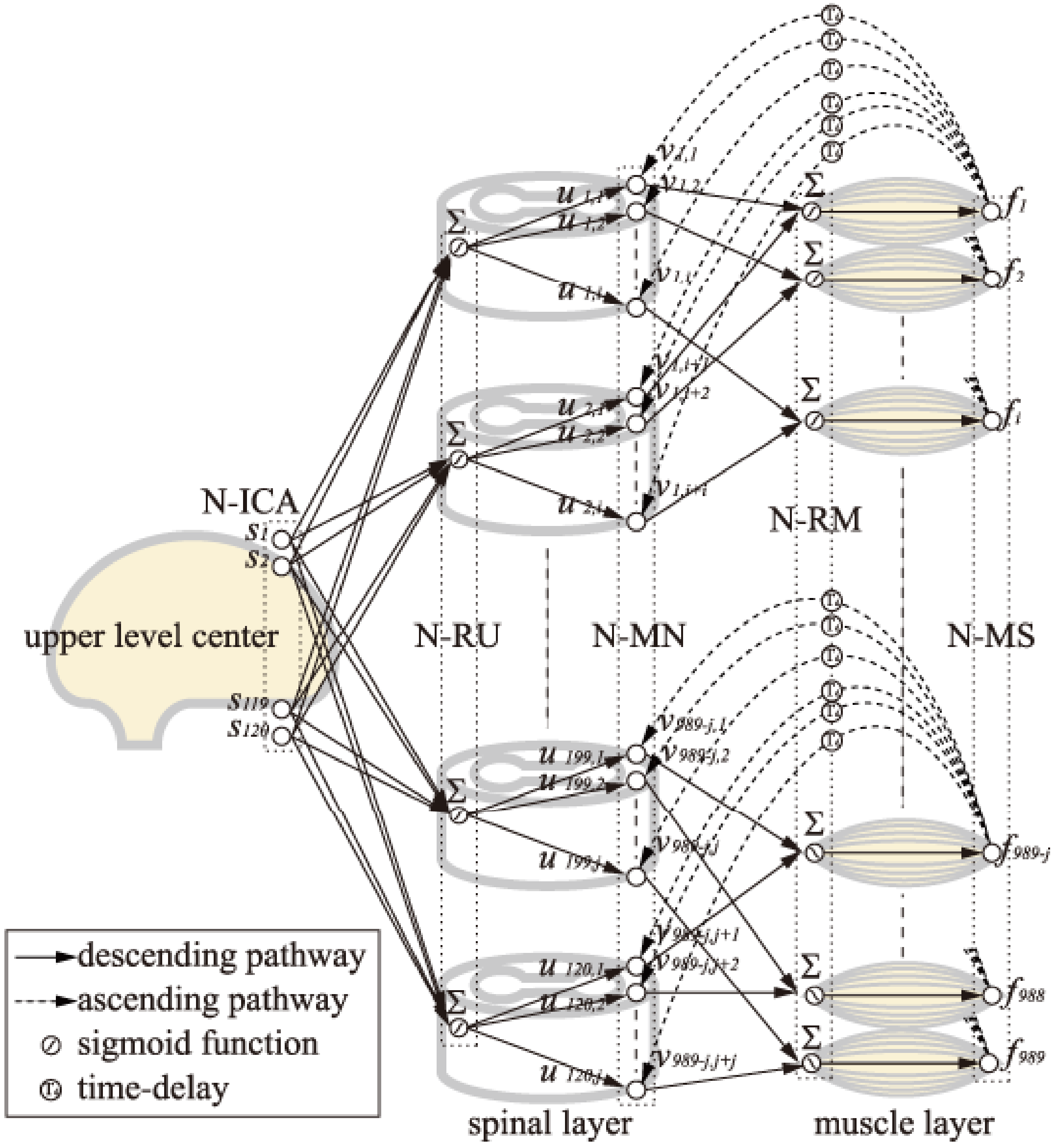
muscle tensions

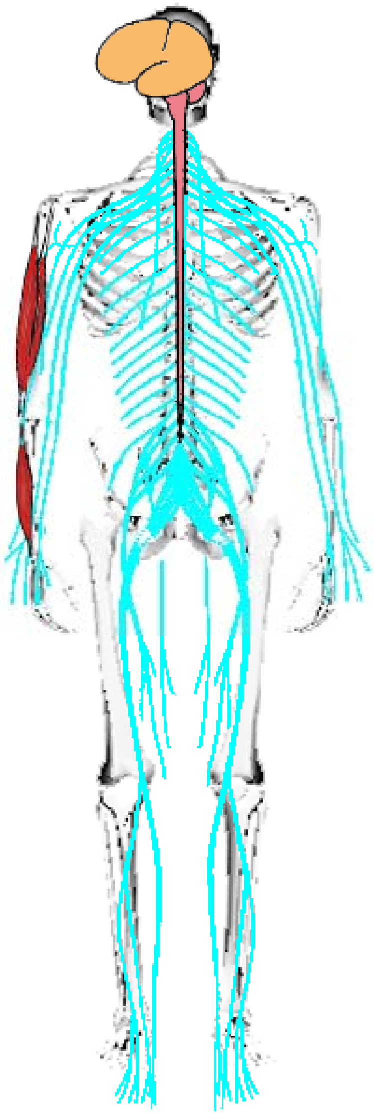
independent signals
=motor command signals

- dimension of $\mathbf{s}$?
  - 120, the number of relevant spinal nerve rami, is enough!

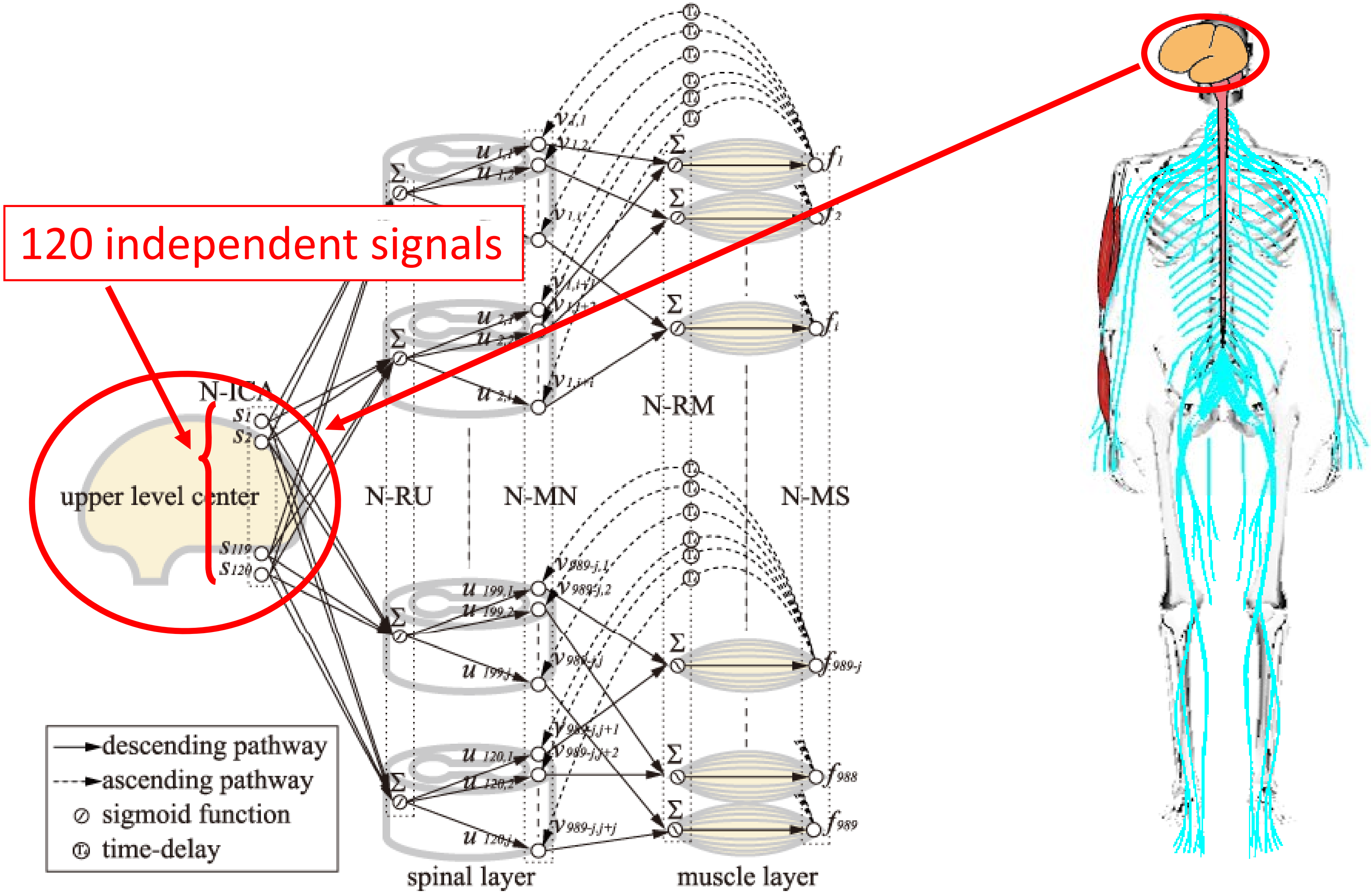


Neuromuscular Network Model



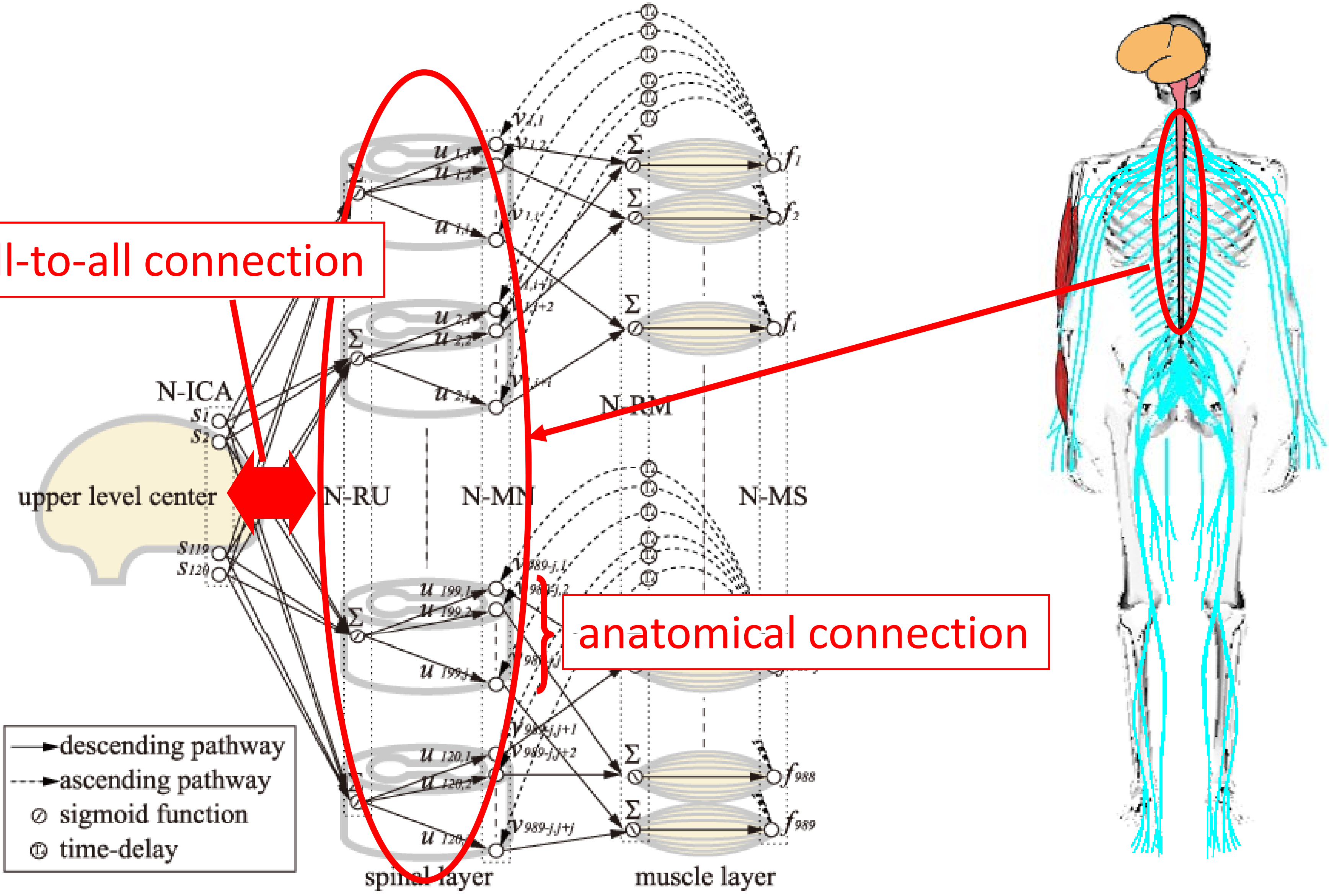


Neuromuscular Network Model



120 independent signals

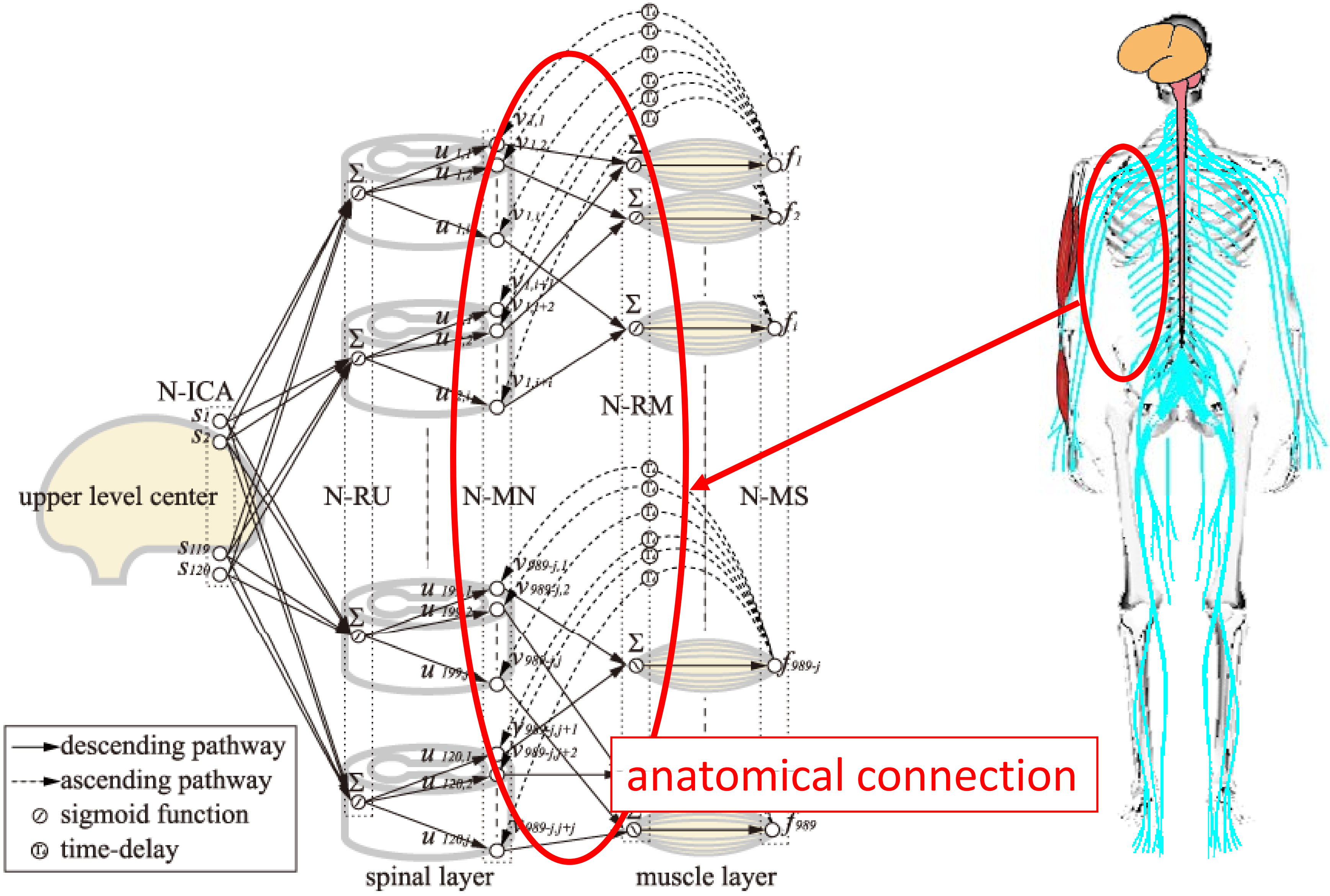
Neuromuscular Network Model



all-to-all connection

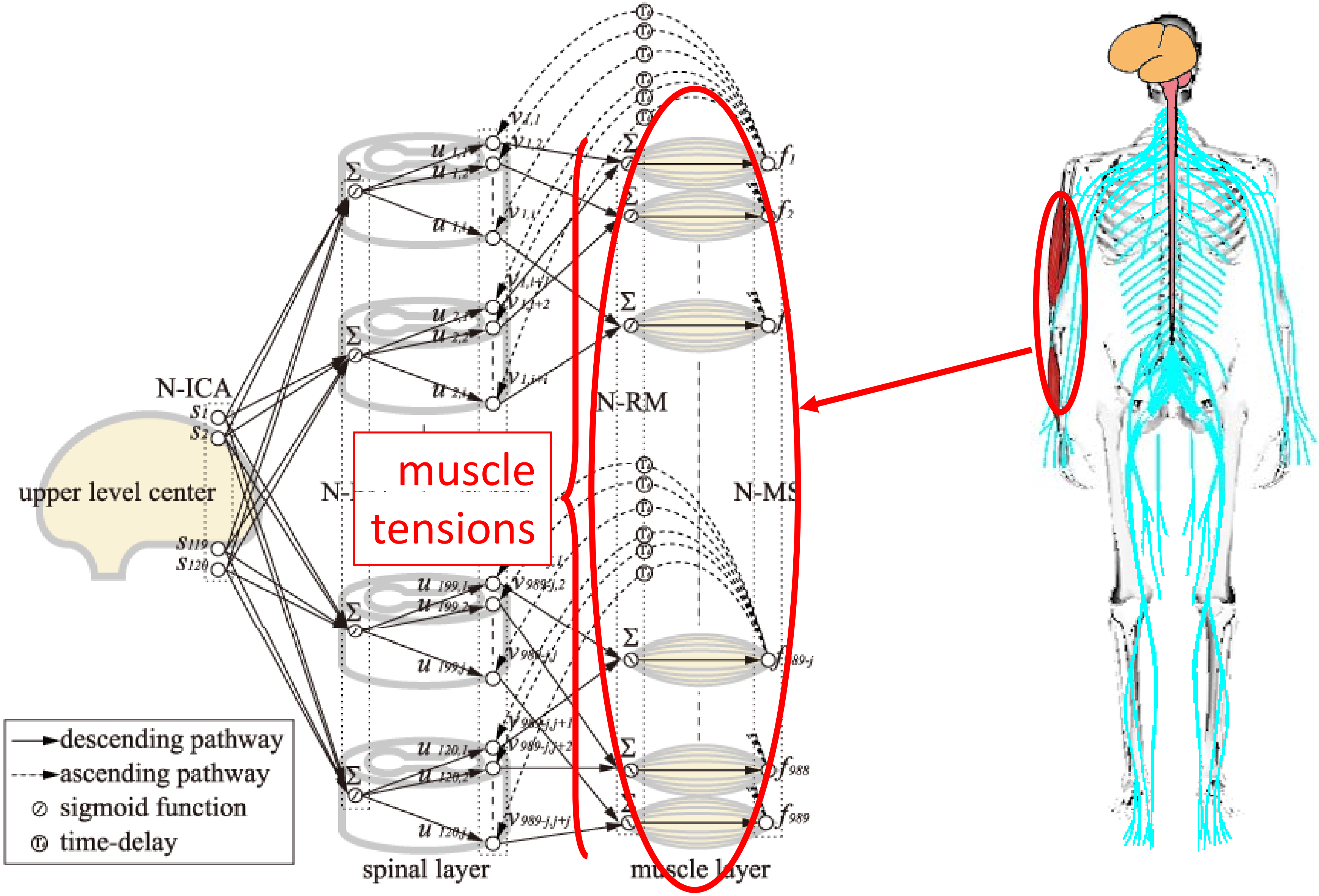
anatomical connection

Neuromuscular Network Model



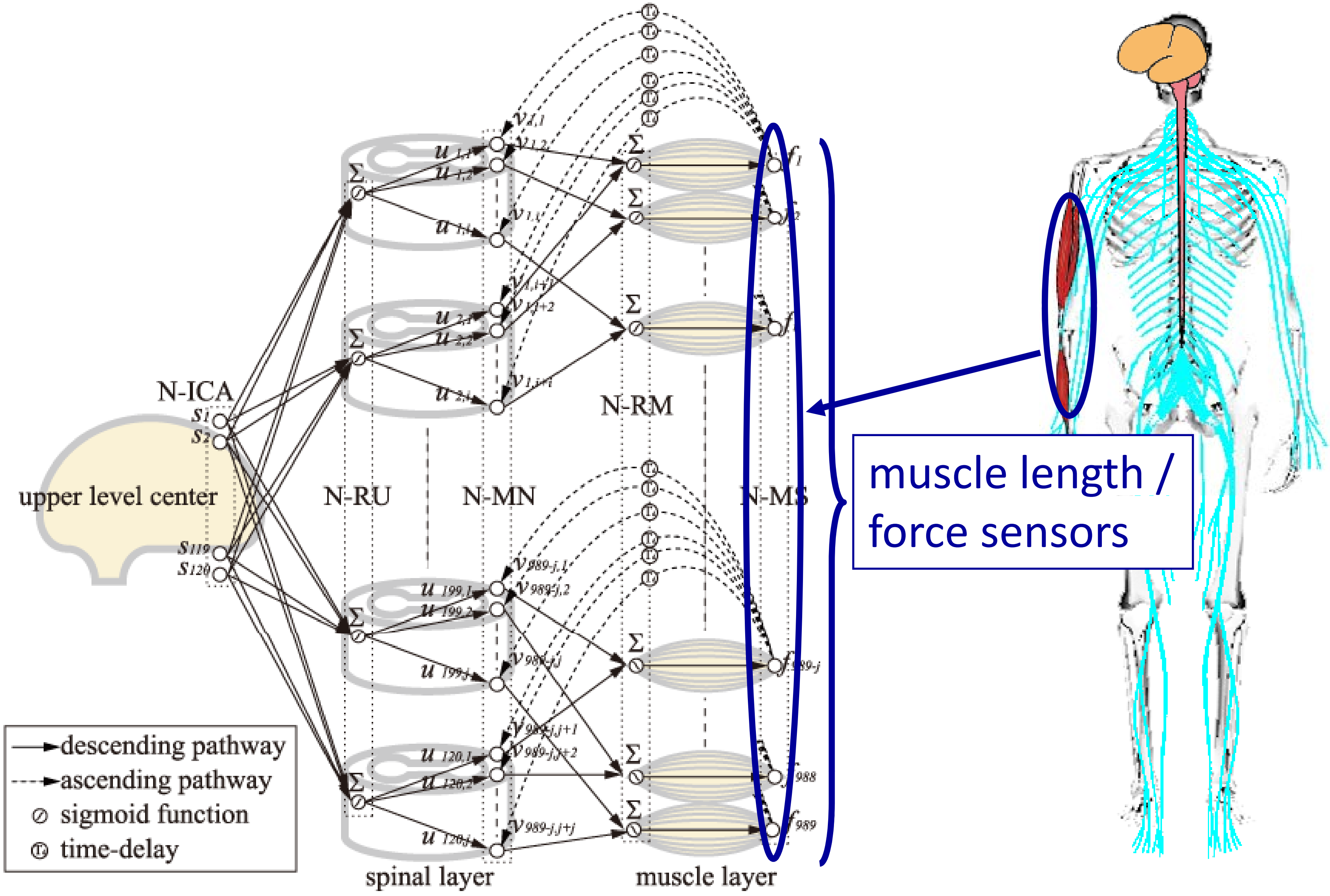
anatomical connection

Neuromuscular Network Model



muscle tensions

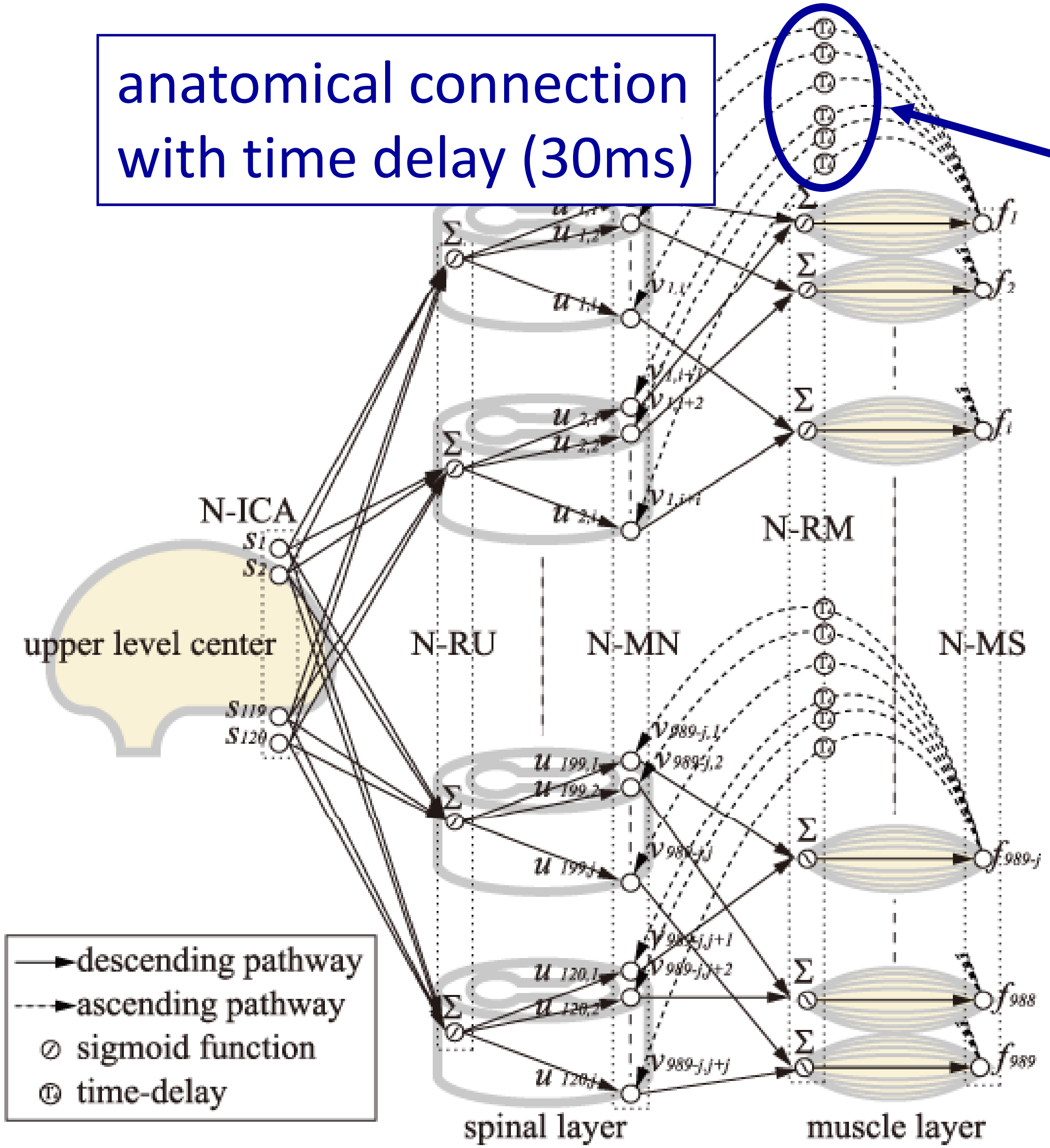
Neuromuscular Network Model

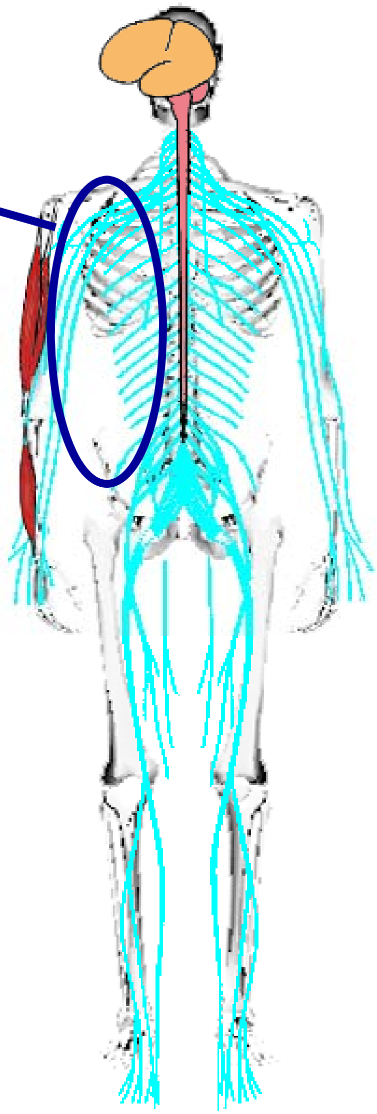


muscle length / force sensors

Neuromuscular Network Model

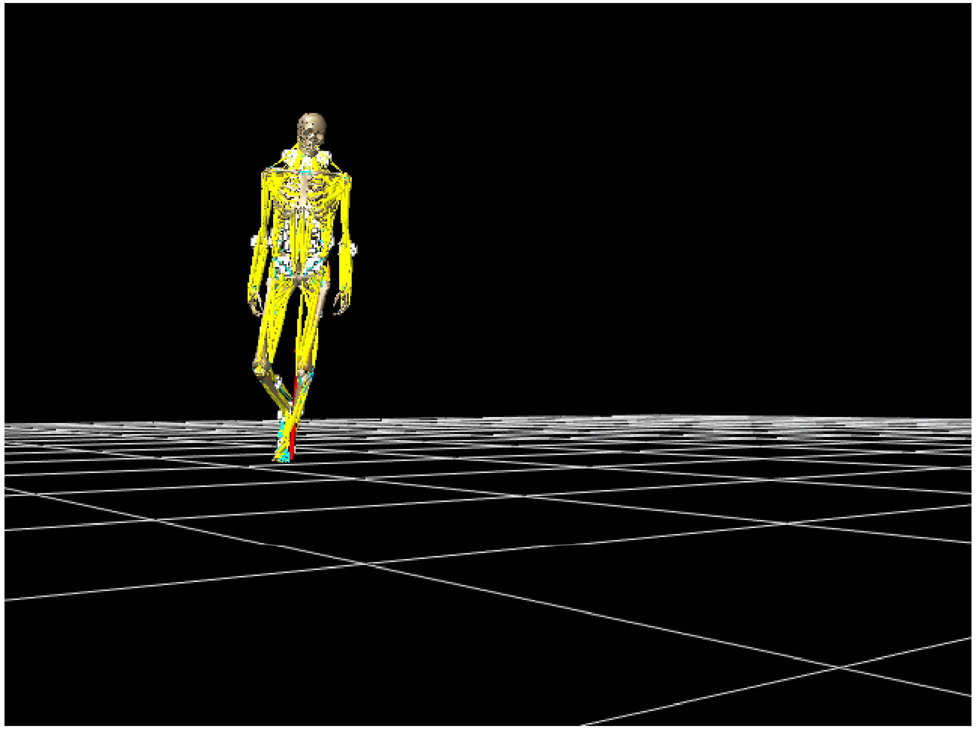
anatomical connection with time delay (30ms)





Identification

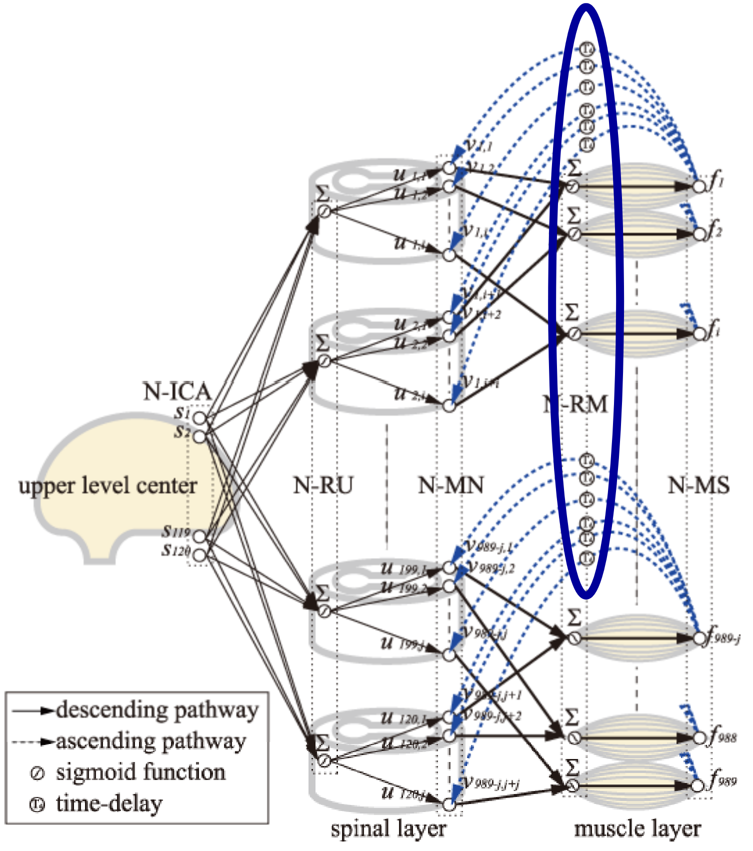
- training data
  - walk (2000 frames, 10 seconds)
  - muscle tensions from inverse dynamics
  - independent signals from ICA
- training
  - 5000 cycles
  - error
    - average: 2.59%
    - variance: 0.34%



Results: Weight Parameter of Reflex Loop

- from Iliacus: agonist for hip flexion

Iliacus	
muscle	weight
Iliacus	4.20E+00
Sartorius	2.60E-01
Rectus Femoris	3.94E+00
Pectineus	4.60E-01
Gracilis	-4.06E-01
Adductor Longus	-1.69E-01
Adductor Brevis	-3.59E-01
Adductor Magnus	-4.10E-02

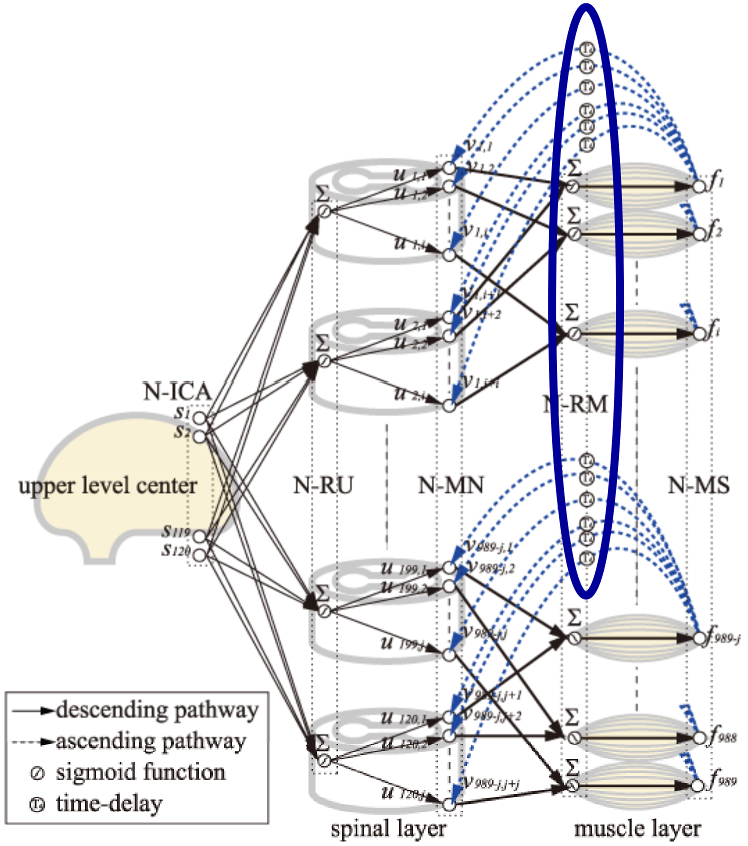


🟦 classified as agonist muscles
for hip flexion in sports science

Results: Weight Parameter of Reflex Loop

- from Tensor Fasciae Latae: agonist for hip flexion

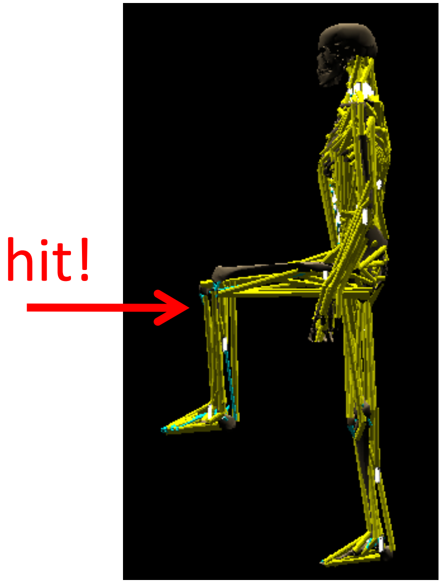
Tensor Fasciae Latae	
muscle	weight
Tensor Fasciae Latae	2.93E-01
Gluteus Maximus	-1.28E-01
Biceps Femoris	-4.53E-01
Semitendinosus	-1.02E+00
Semimembranosus	-1.13E+00
Gluteus Medius	-4.94E-02
Gluteus Minimus	-9.30E-01

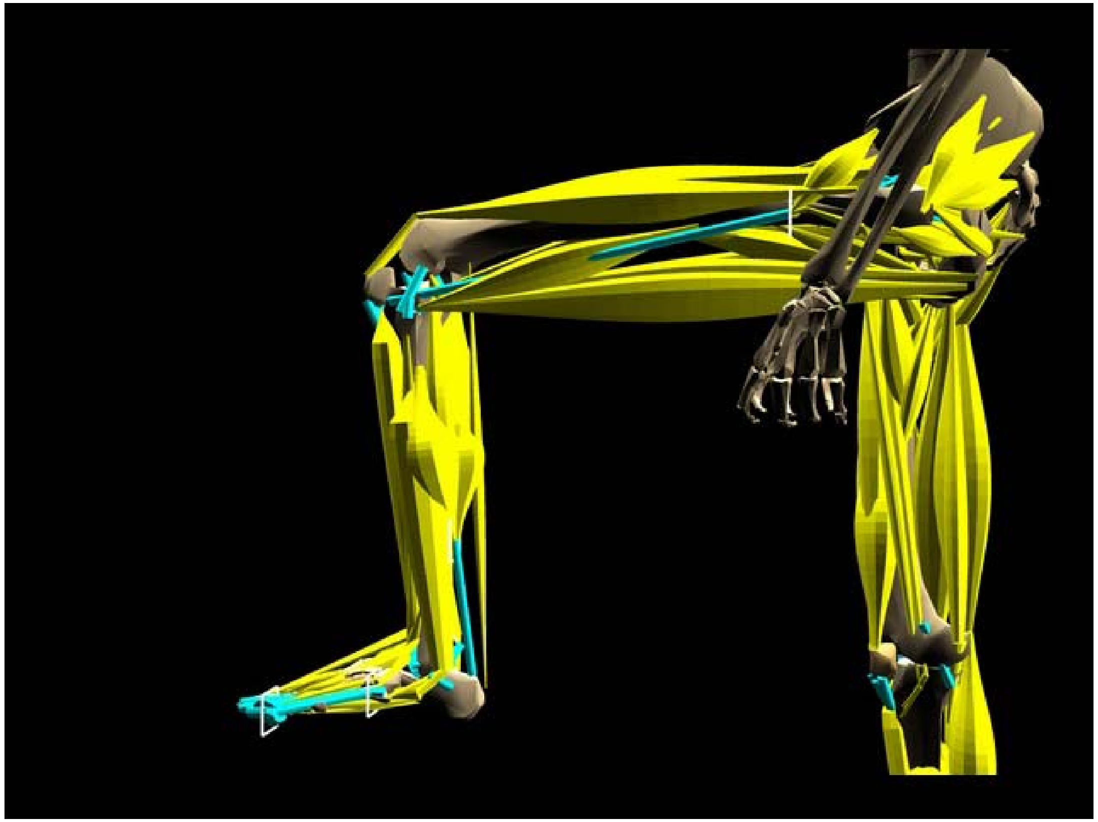


🟨 classified as antagonist muscles
for hip flexion in sports science

Results: Patellar Tendon Reflex

- patellar tendon reflex: stretch reflex of quadriceps





Summary

- motion adaptation techniques
  - dynamics filter: adaptation to small differences in kinematics and dynamics
  - synthesizing manipulation tasks: adaptation to different kinematics and environment
  - motorized marionette: completely different kinematics and actuation mechanism

- understanding human adaptation
  - musculoskeletal and neuromuscular network models

Acknowledgements

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    - dynamics filter
    - neuro-musculoskeletal human model

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- CMU Graphics Lab
    - synthesizing manipulation tasks
    - motorized marionette