# Human Simulation and the Deep Learning of Neuromuscular and Sensorimotor Control

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*and VoxelCloud, Inc.*

# Virtual Humans in the Movies

## *These characters are neither autonomous nor intelligent*

*"Final Fantasy: The Spirits Within"*
(Square Pictures, Inc., 2001)

*"Beowulf"*
(Paramount/Warner Bros., Inc., 2007)

# Human Characters in Interactive Games

*Metal Gear Solid*

# Motion Capture Technology

## 3D tracking of body-attached IR reflectors

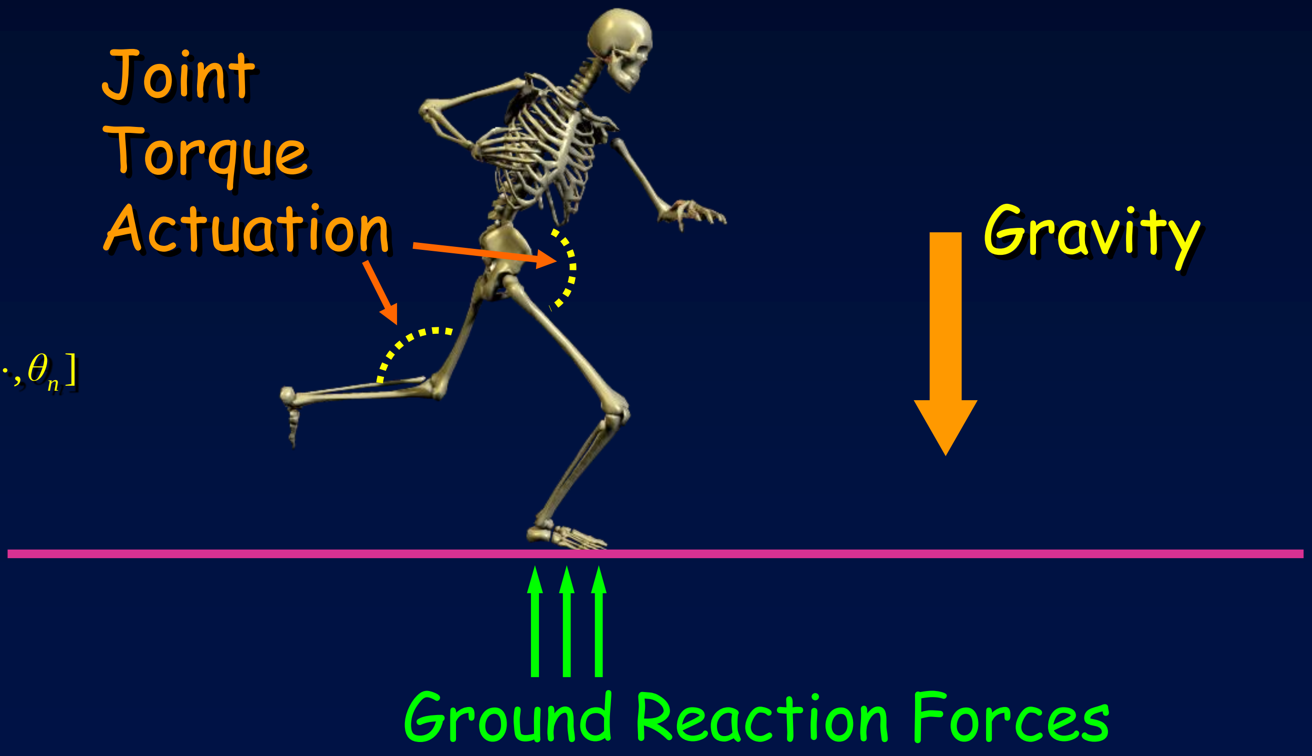
# Simplistic Biomechanical Models

## *Articulated anthropomorphic figures*

- Physical properties consistent with fully-fleshed humans

System DOFs: $\mathbf{q} = [\mathbf{T}, \mathbf{R}, \theta_1, \cdots, \theta_n]$

State $= [\mathbf{q}, \dot{\mathbf{q}}]$



# Physics-Based Whole-Body Simulation

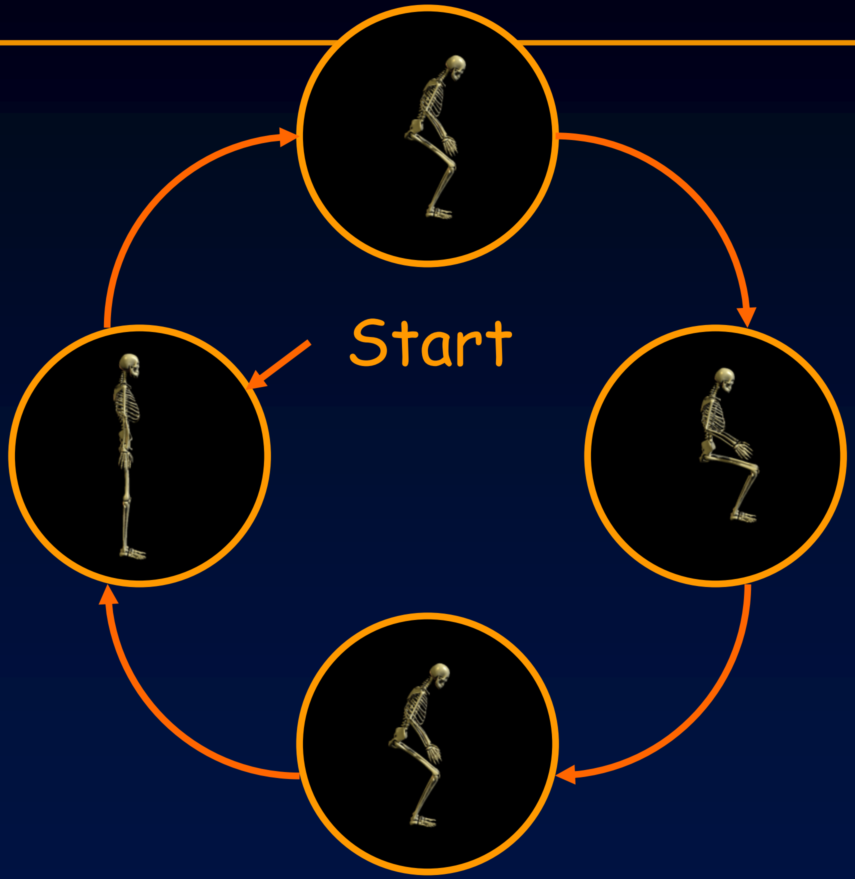
## *The virtual stuntman*

[Faloutsos, van de Panne, Terzopoulos 2001]

# Pose Controllers

**Example:**

**Sit / Stand**




$$\theta_1 \quad \rightarrow \quad \tau_1 = k_s^1(\theta_1 - \theta_{1,desired}) - k_d^1\dot{\theta}_1$$

$$\vdots$$

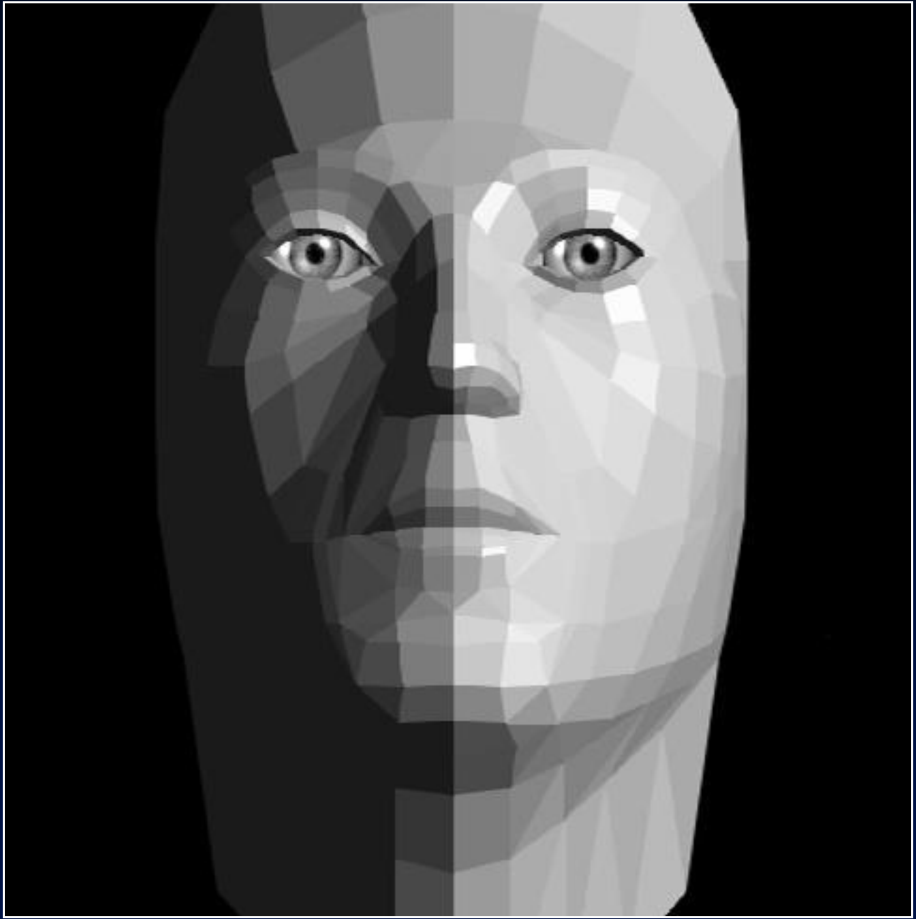
$$\theta_n \quad \rightarrow \quad \tau_n = k_s^n(\theta_n - \theta_{n,desired}) - k_d^n\dot{\theta}_n$$

# Falling Backward, Rolling Over, Rising, and Balancing in Gravity

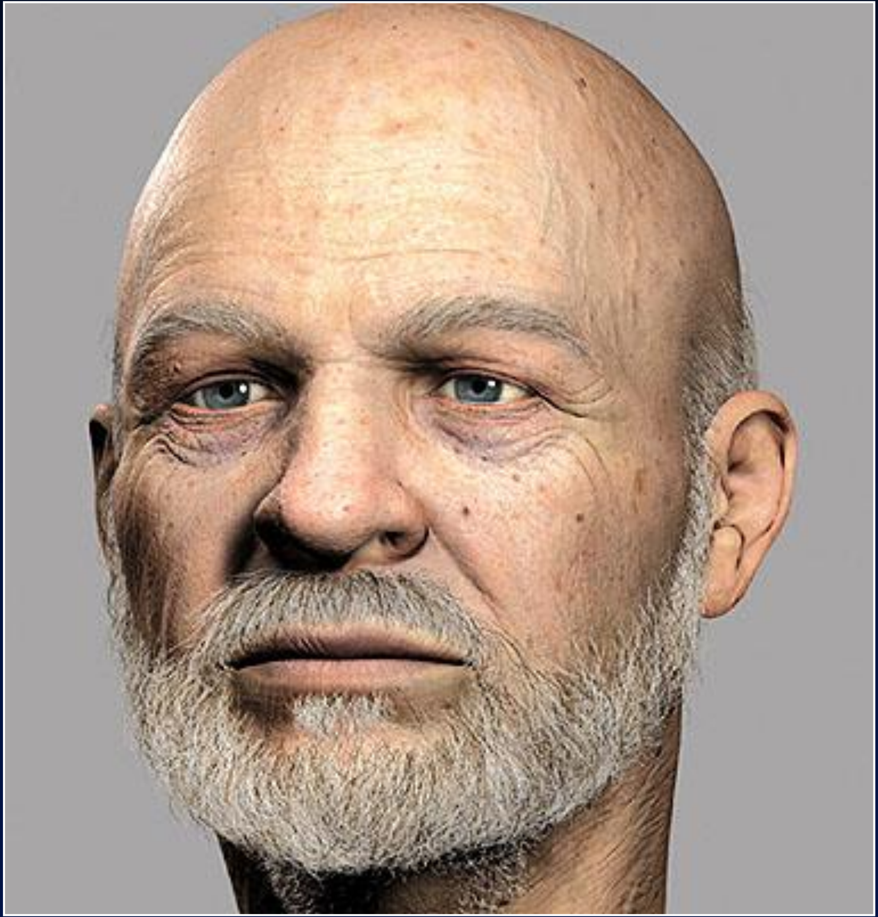
*Help, I've fallen! … and I can get up!*

# 20 Years of Facial Modeling

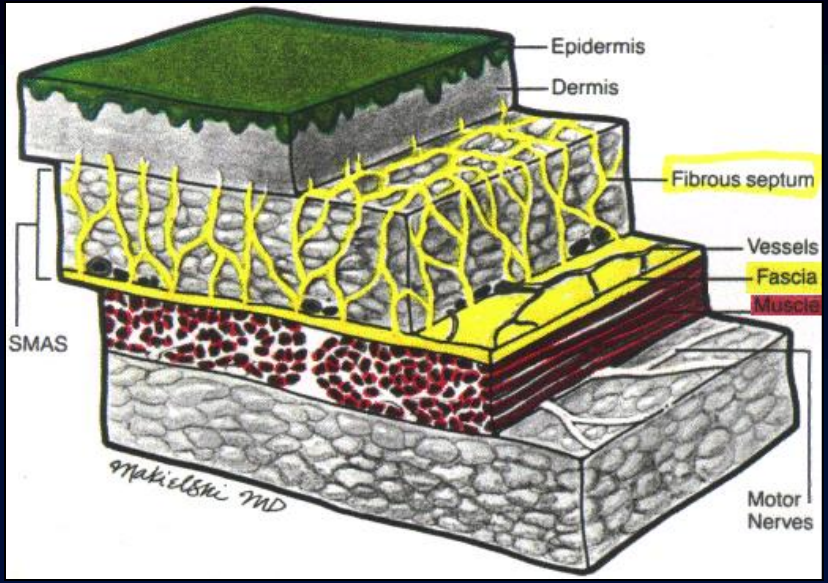
*Parke & Williams, 1981*

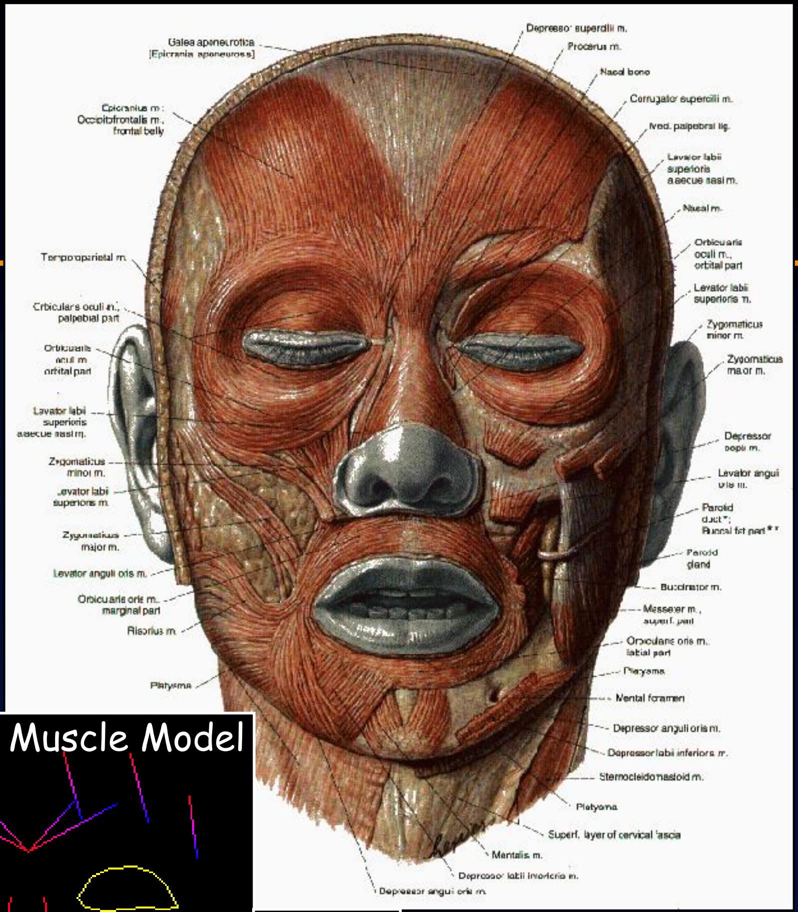


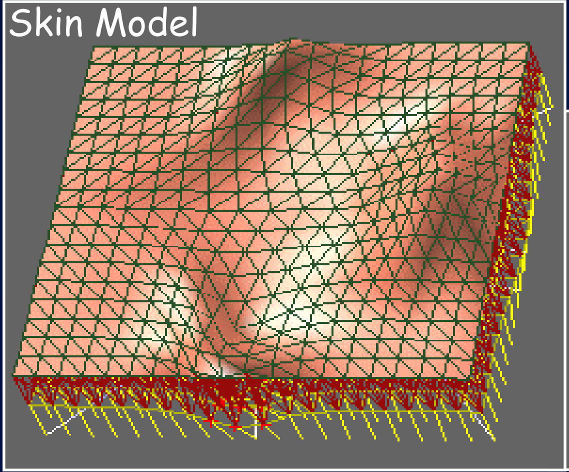
*Square USA, 2001*

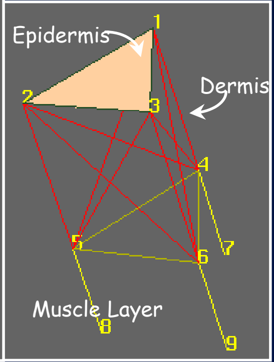


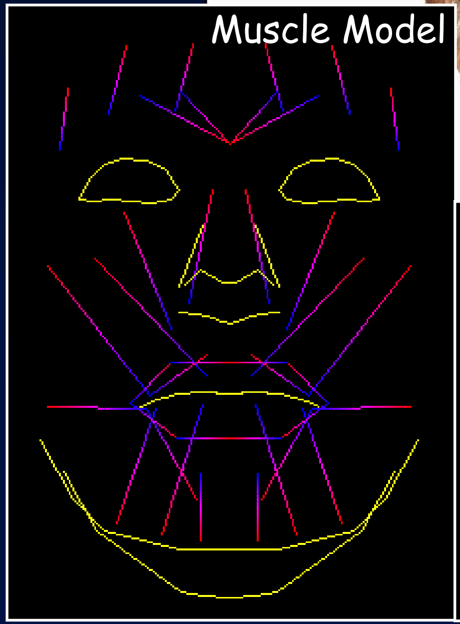
# Facial Anatomy

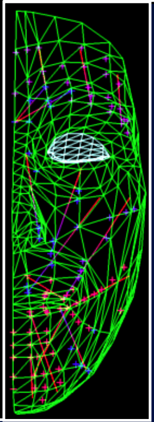


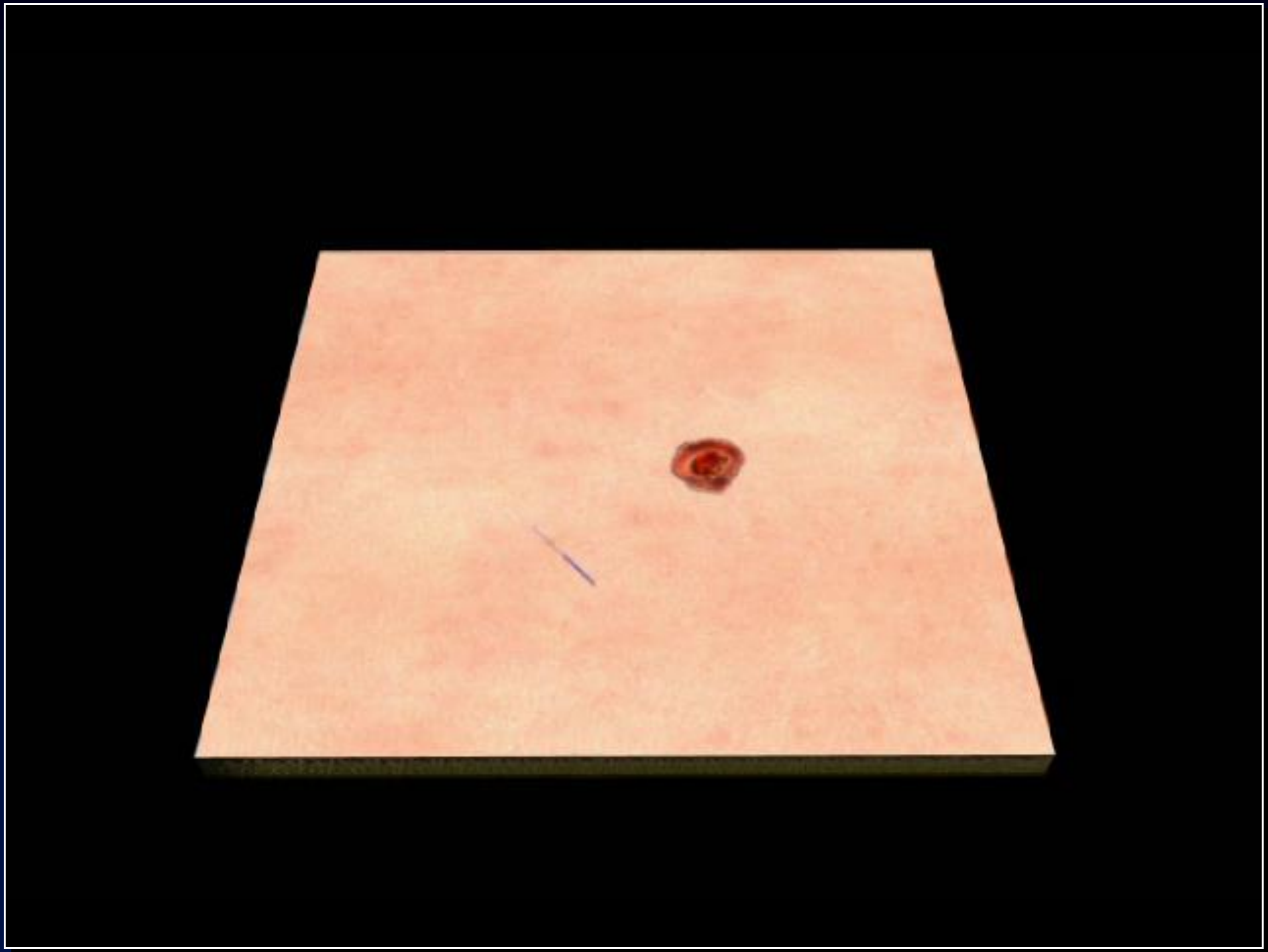
# Real-Time Biomechanical Facial Simulation

[Lee, Waters, Terzopoulos 1995]

# Soft Tissue Simulation

## *Surgery simulation*

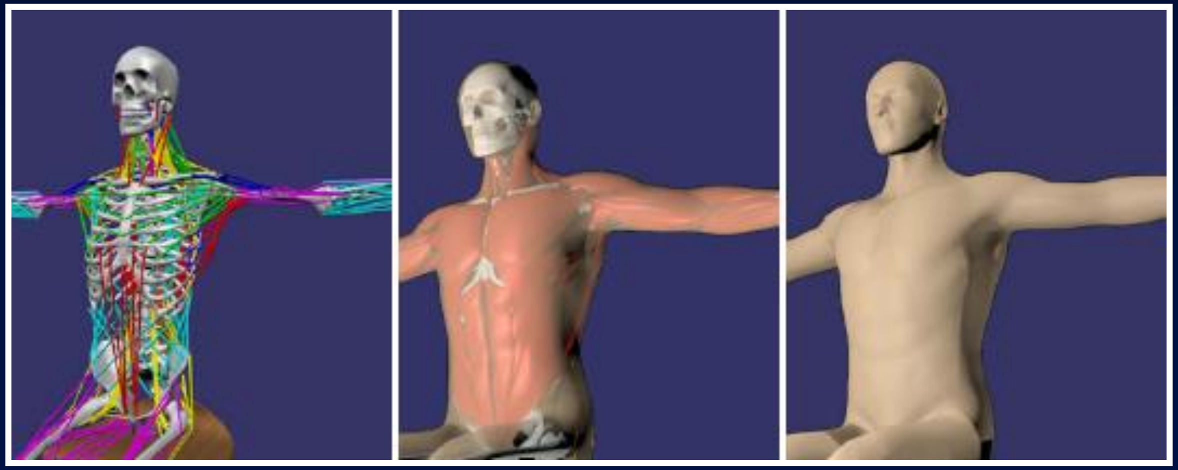
[Sifakis et al. 2009]

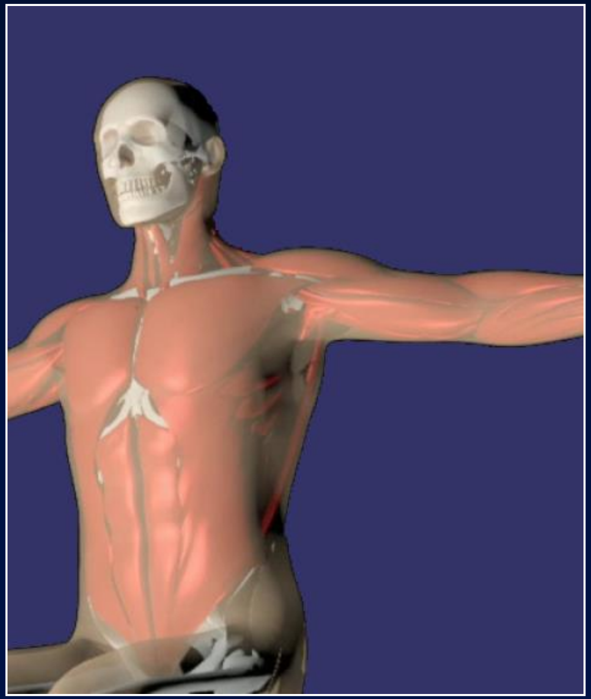


# A Comprehensive, Realistic Biomechanical Musculoskeletal Model of the Human Body

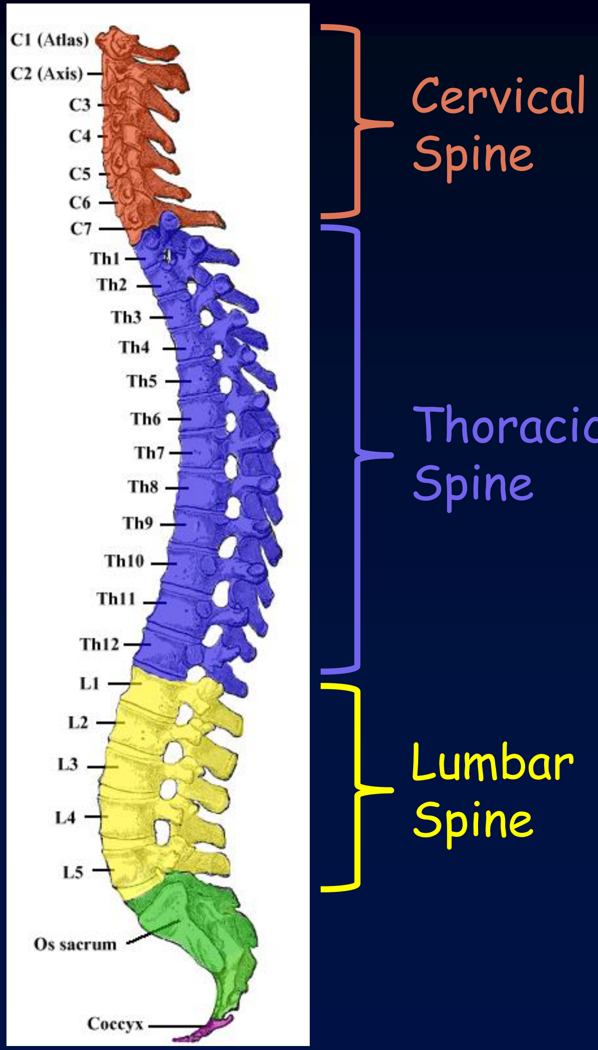
- Almost all the articular bones and skeletal muscles
  - *75 bones (165 DOFs), 846 muscles*
- Volumetric finite element soft tissue model
  - *354K tetrahedral elements*

[Lee, Sifakis, Terzopoulos 2009]

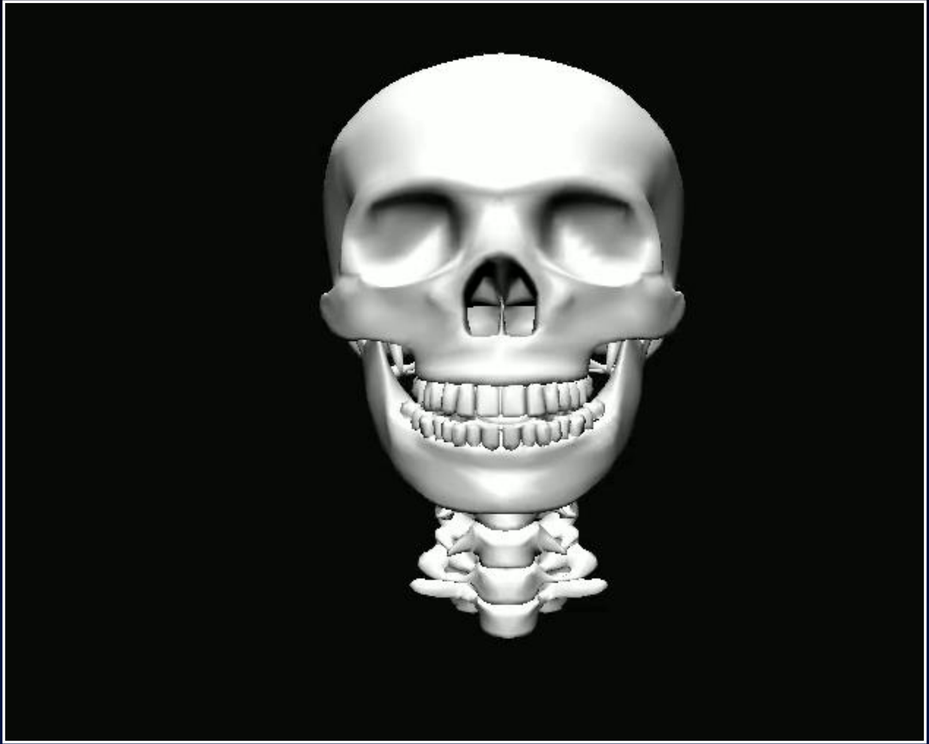


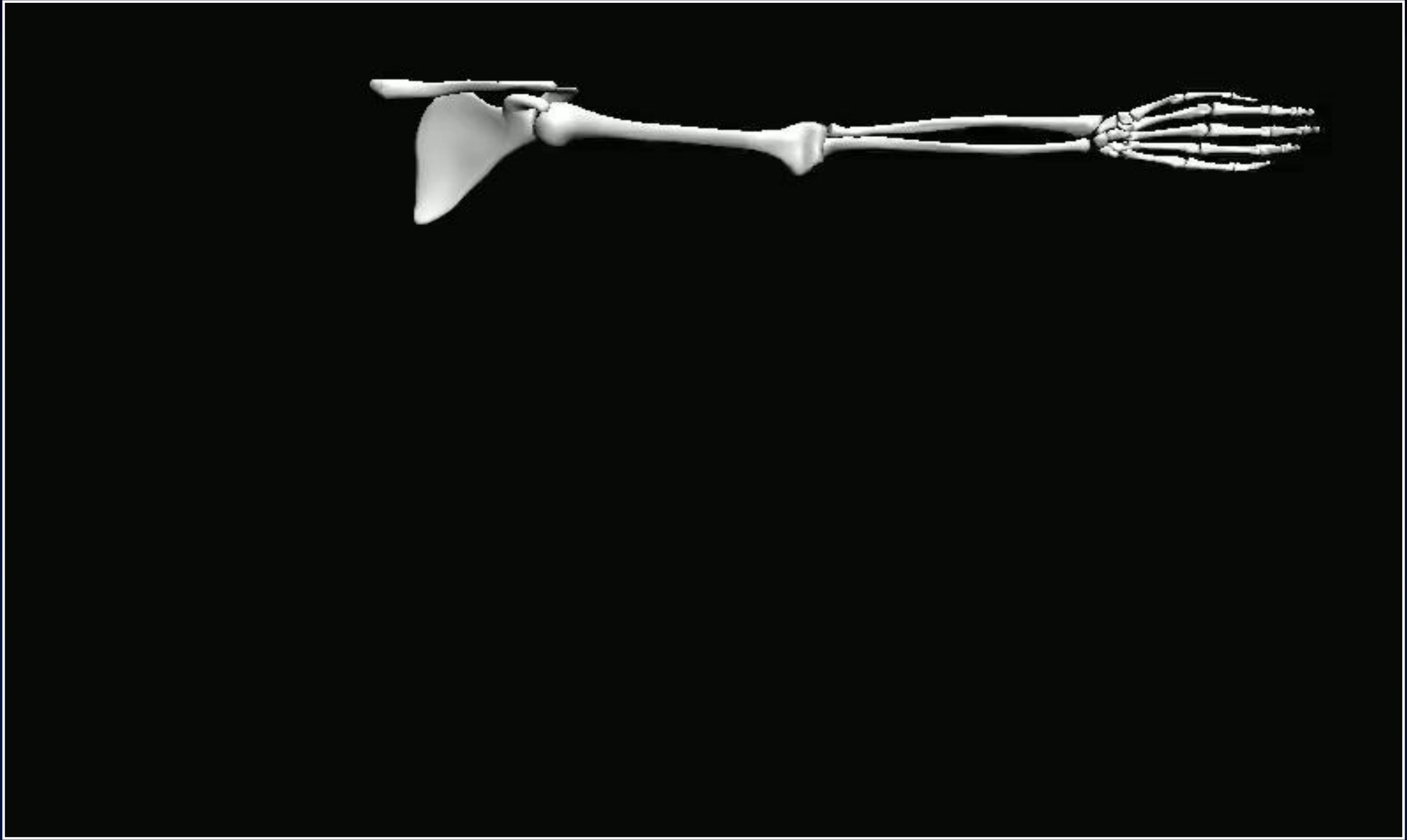


# The Skeletal Model



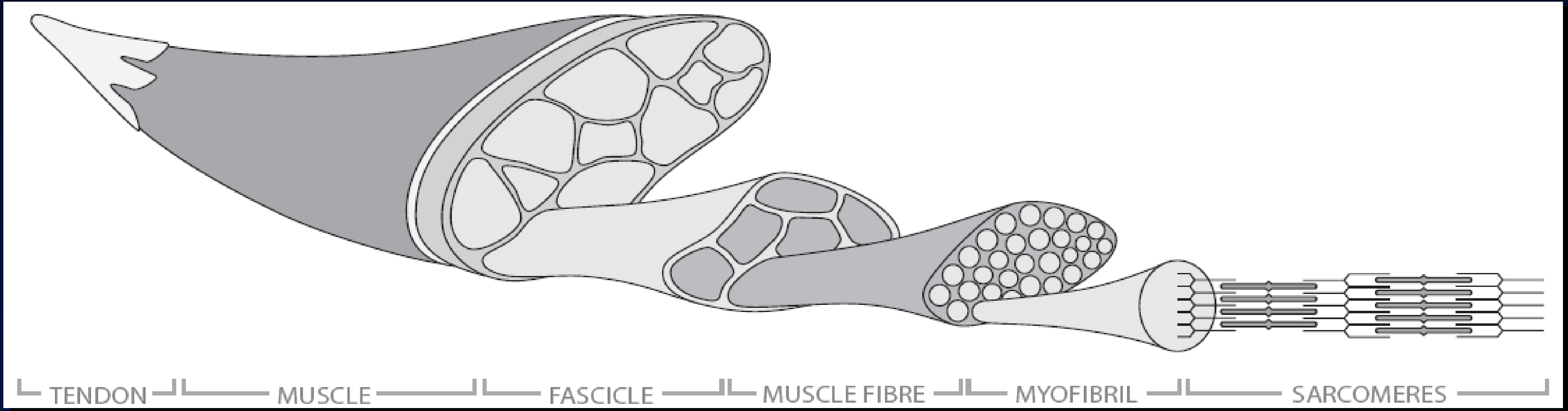
# Skeletal Forward Dynamics

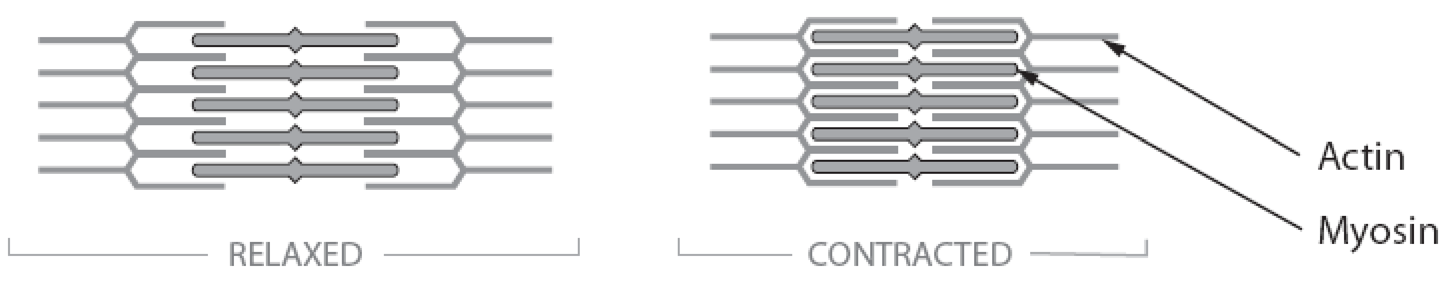




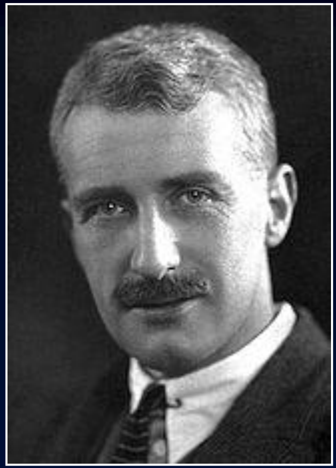
# Muscles

## *Components of the hierarchical muscle structural system*



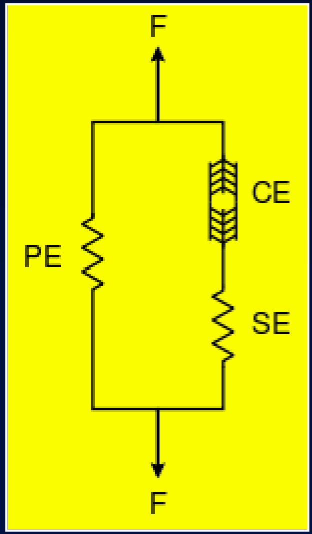
# Hill Muscle Model



## *Physiologist Archibald V. Hill (1886-1977)*

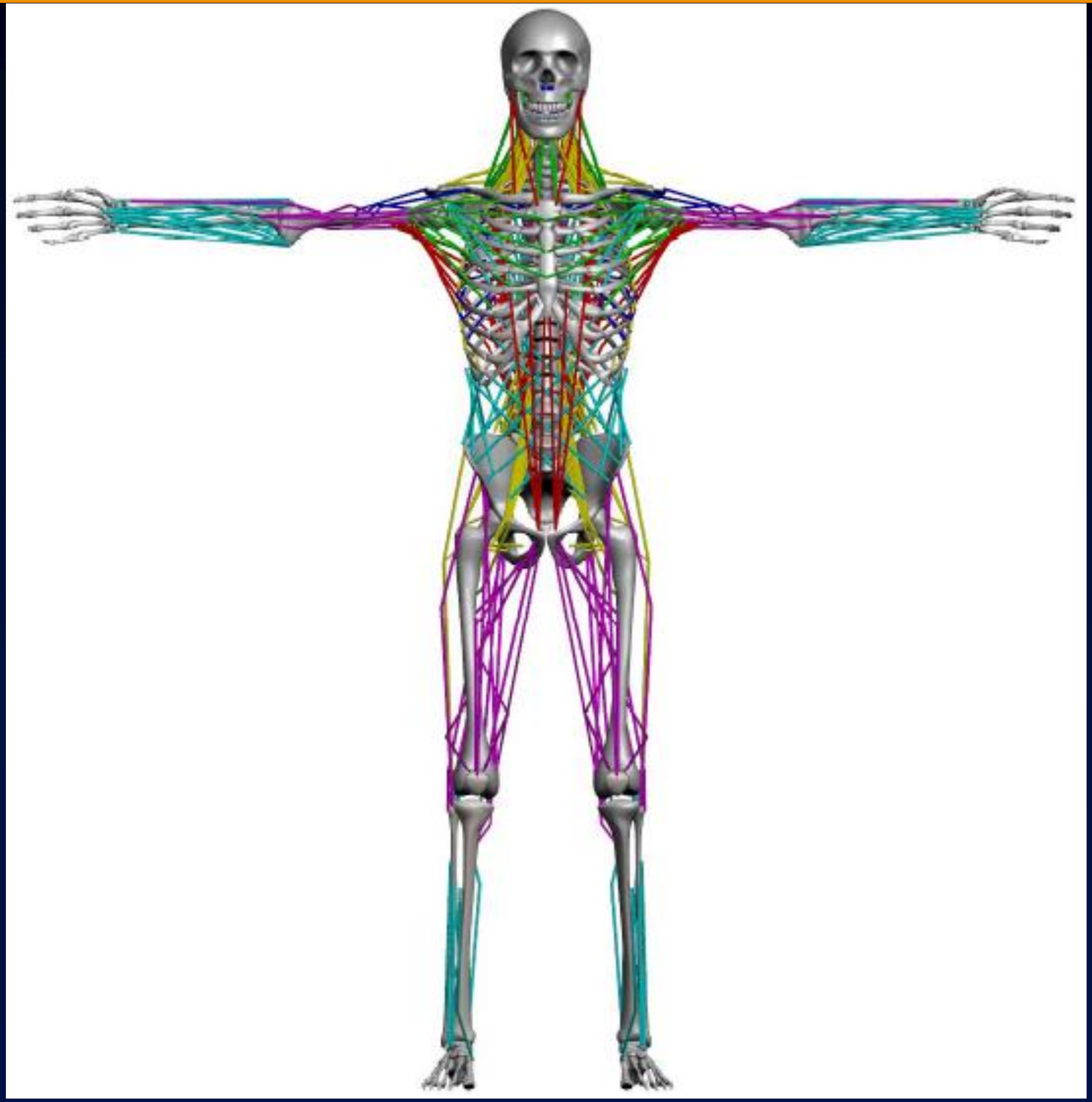
- 1922 Nobel Prize in Physiology or Medicine for elucidation of mechanical work produced in muscles

- Uniaxial model
  - *CE: Contractile Element*
  - *SE: Series Element*
  - *PE: Parallel Element*

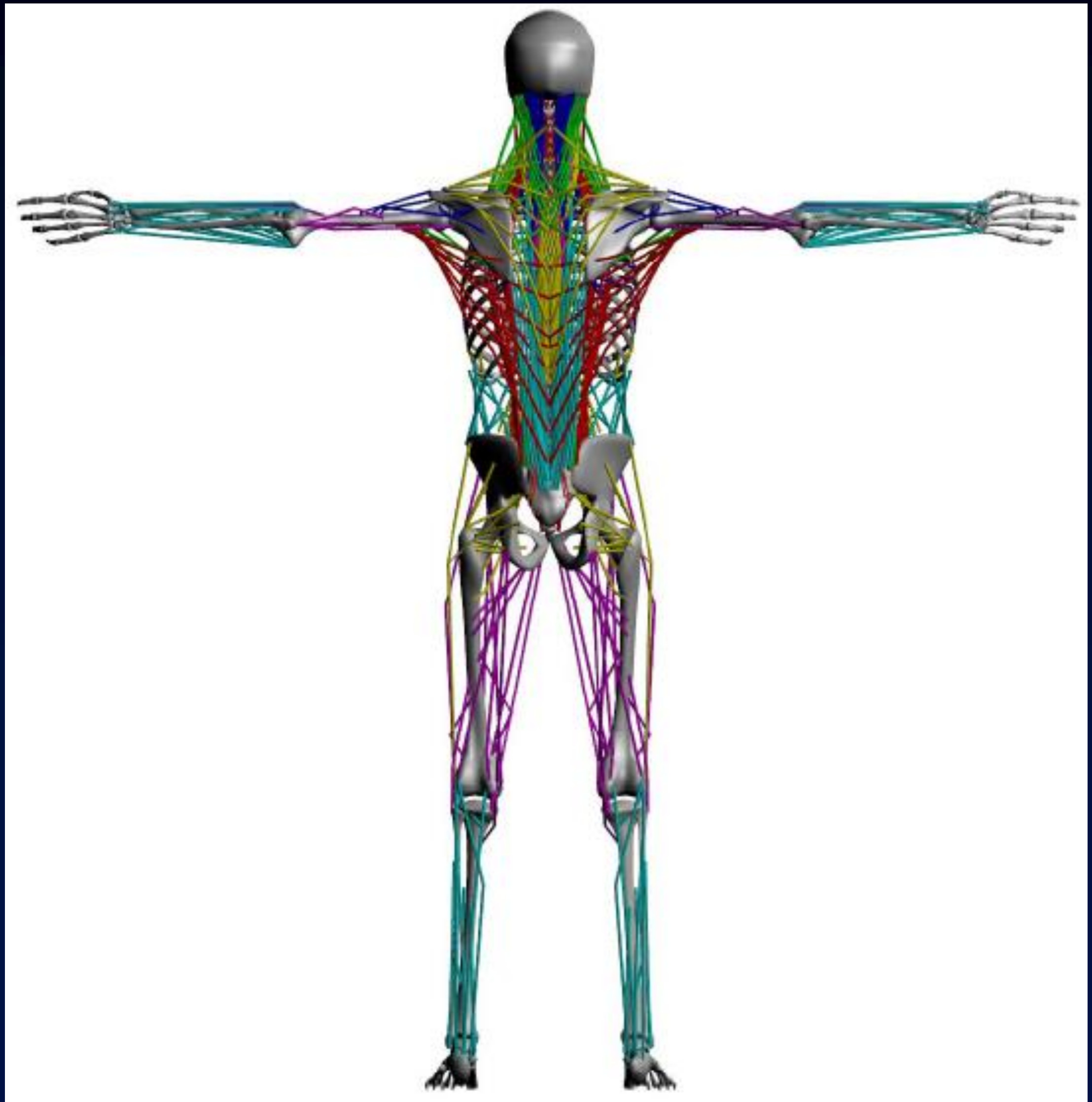



  - *CE driven by activation signal a(t)*

# The Biomechanical Musculoskeletal Model

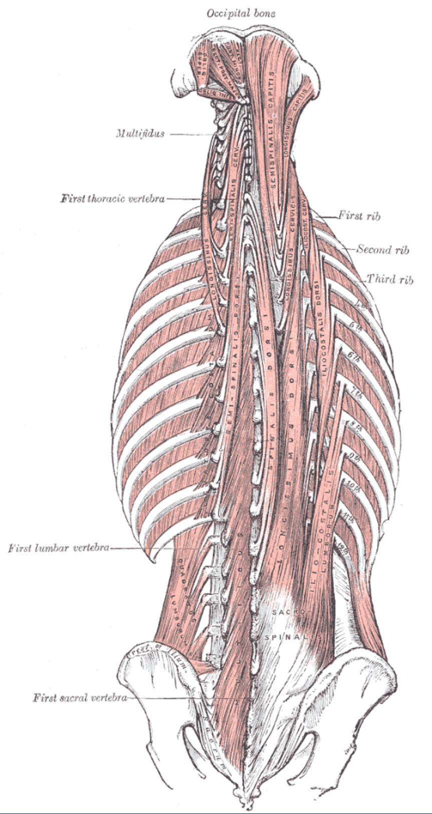


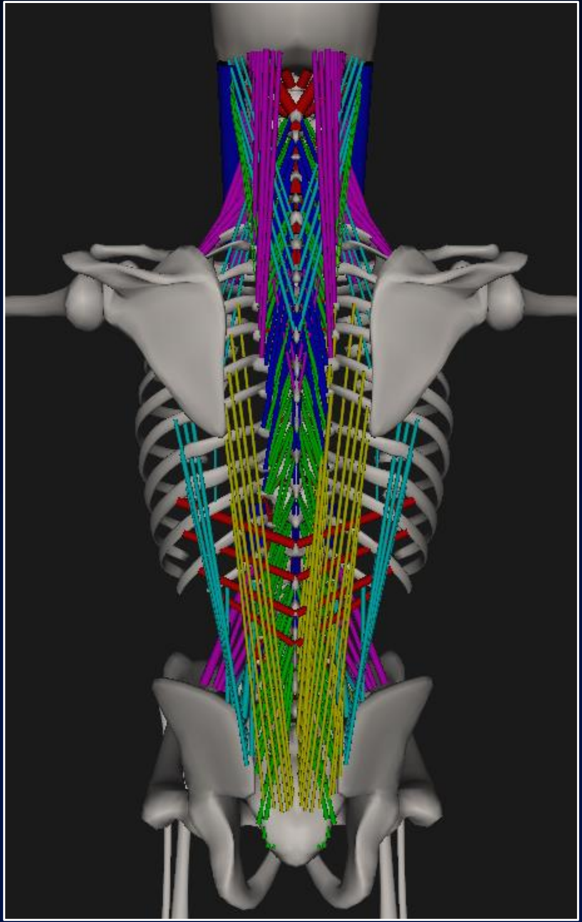
# The Biomechanical Musculoskeletal Model



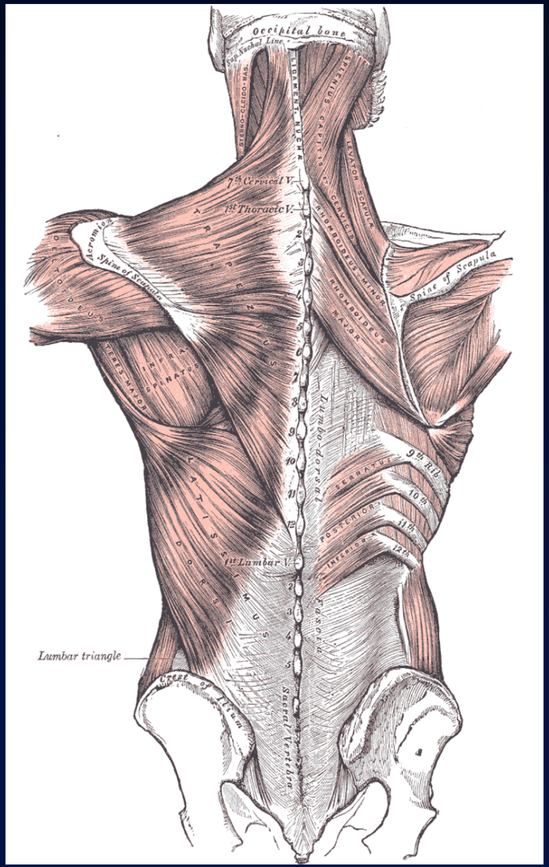
# Posterior Muscles in the Deep Layers

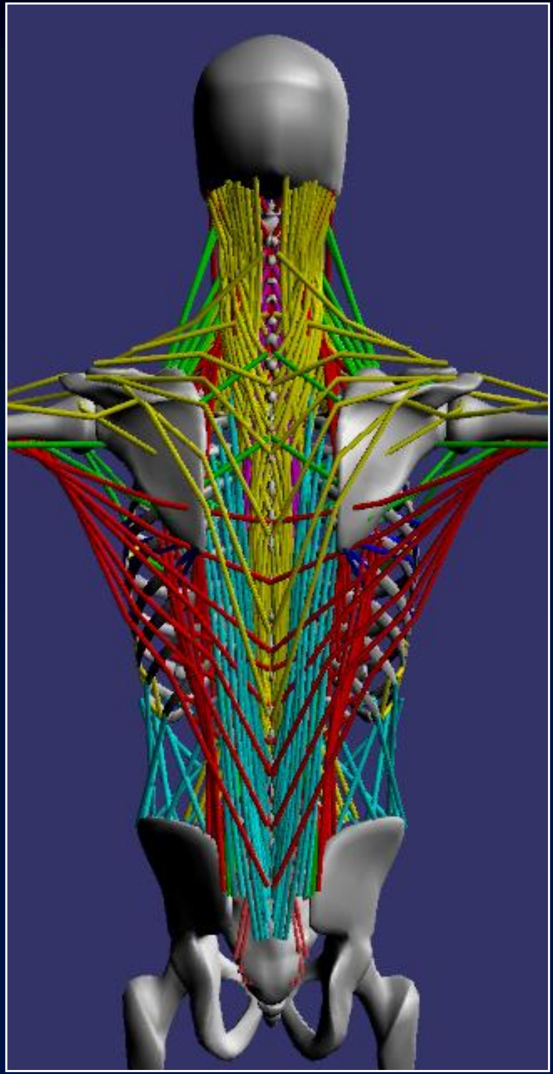
***Modeling all the major muscles participating in spinal posture***

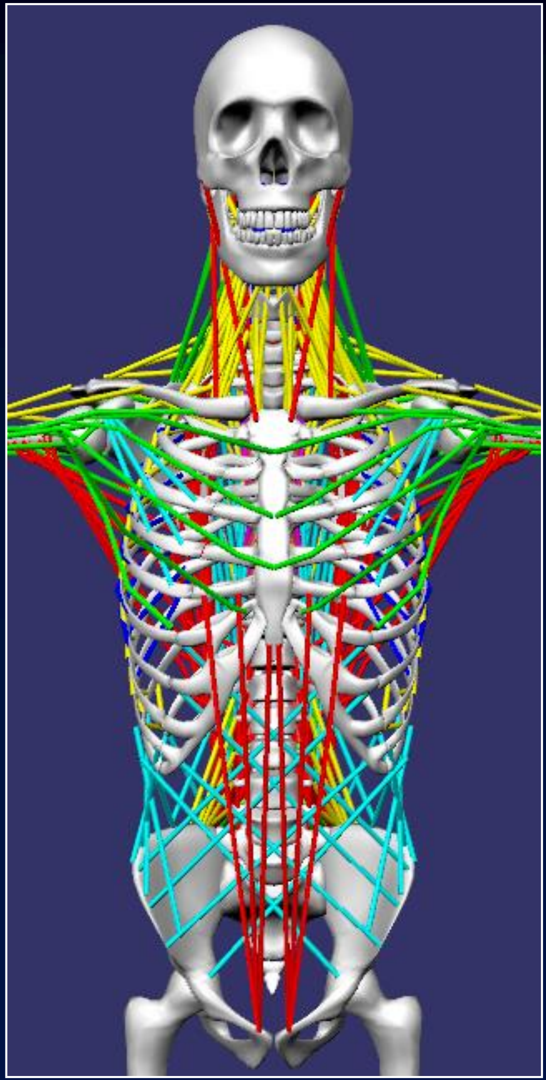


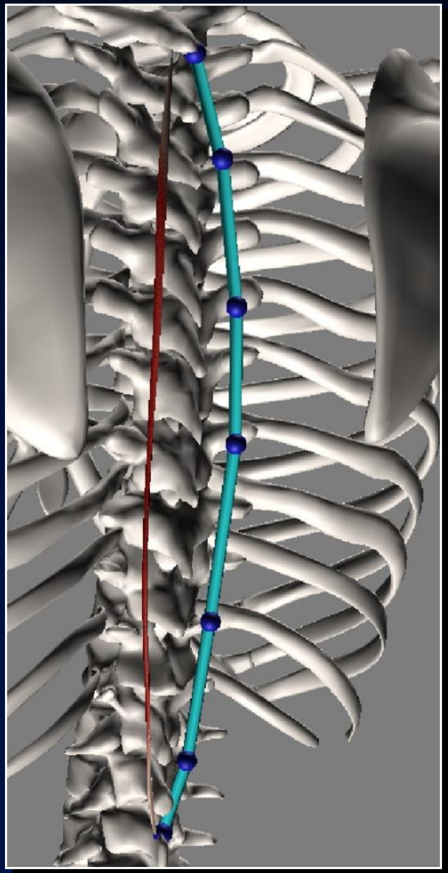
# Upper Body Musculature

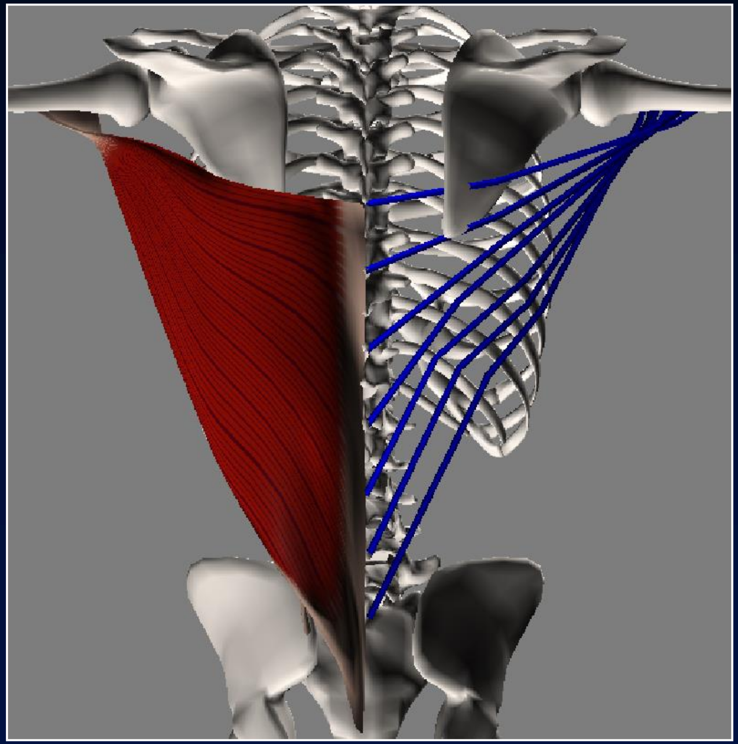




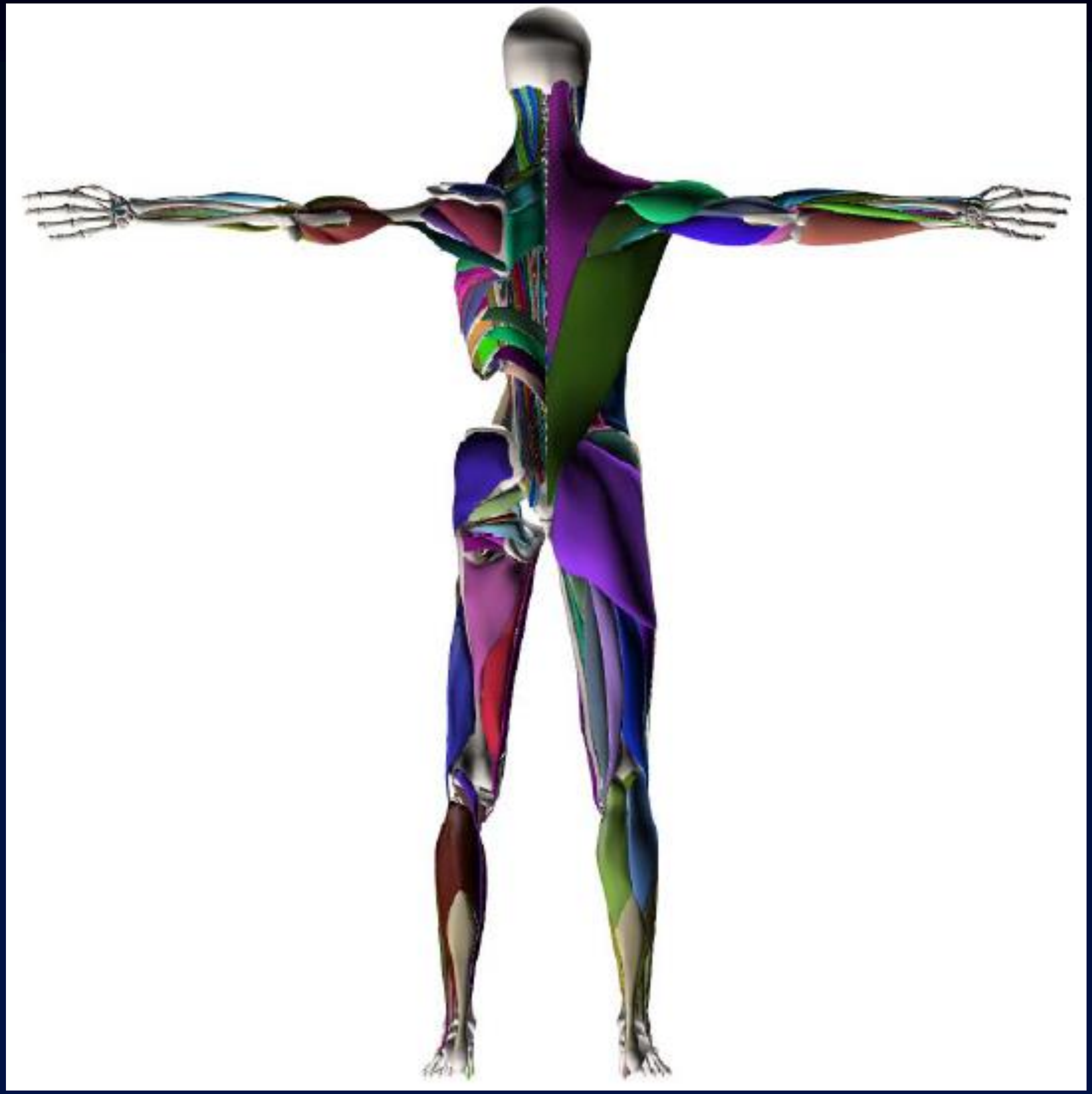
# Piecewise Line Segment Hill-Type Muscle Model



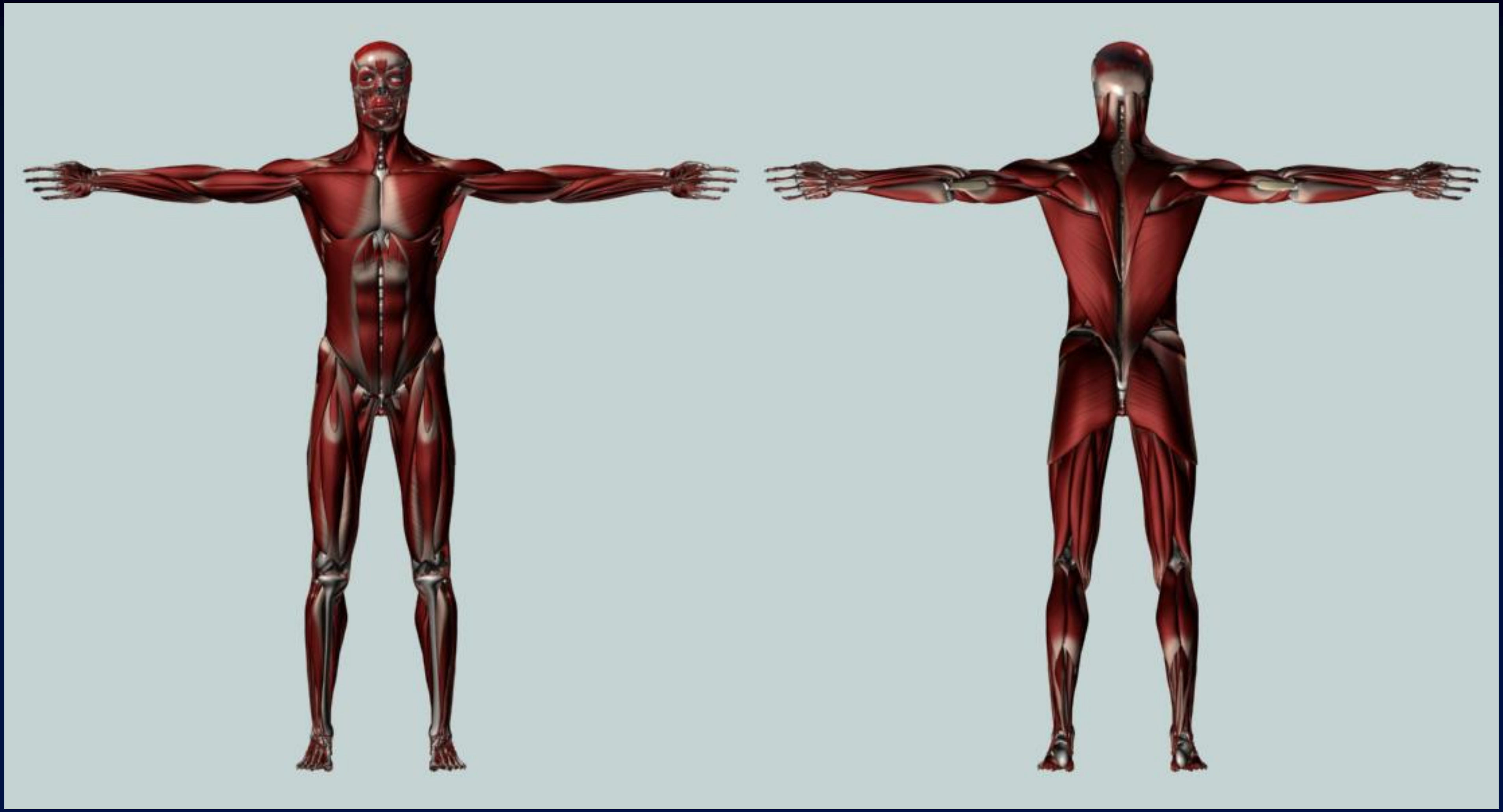


# The Musculoskeletal Model

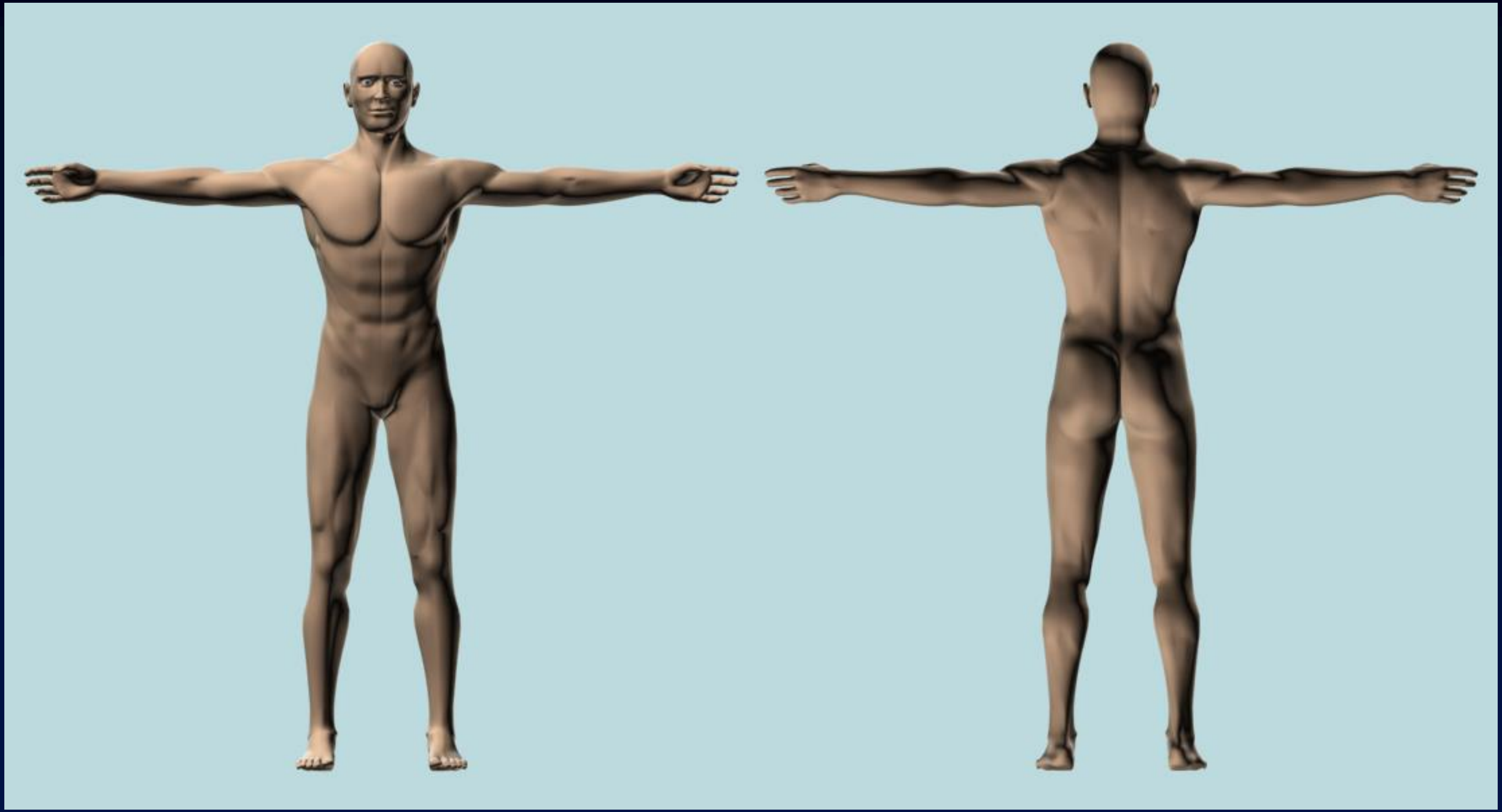
# The Musculoskeletal Model



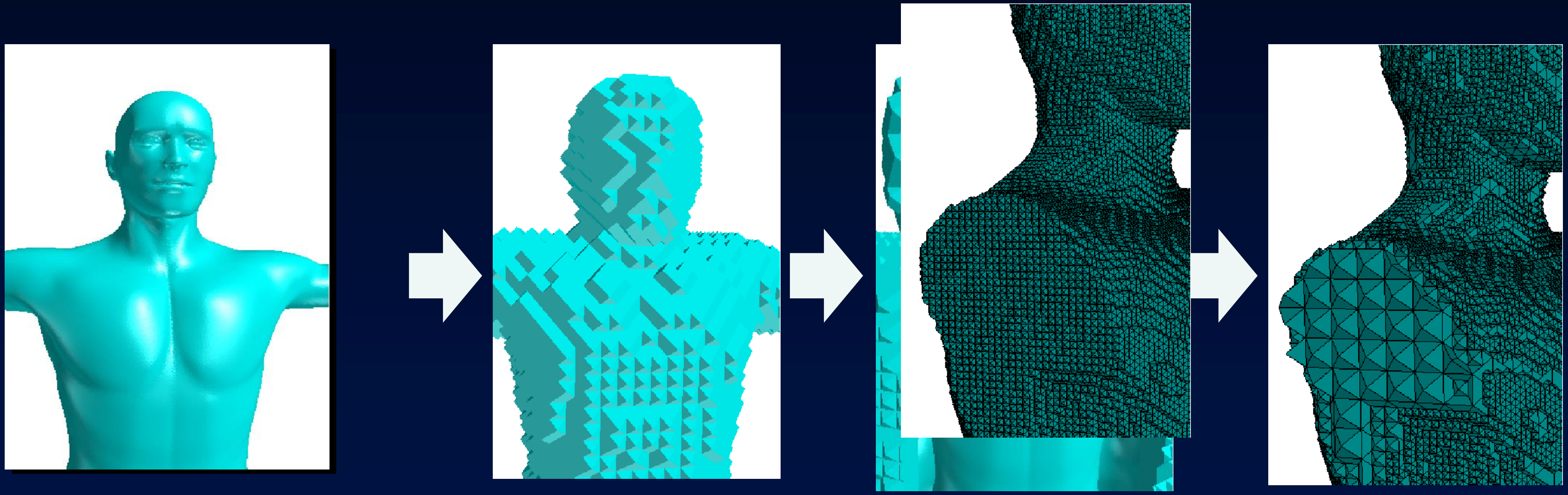
# 3D Muscle Geometries



# Skinned Biomechanical Human Model



# Creating the Soft Tissue Simulation Mesh



Skin geometry

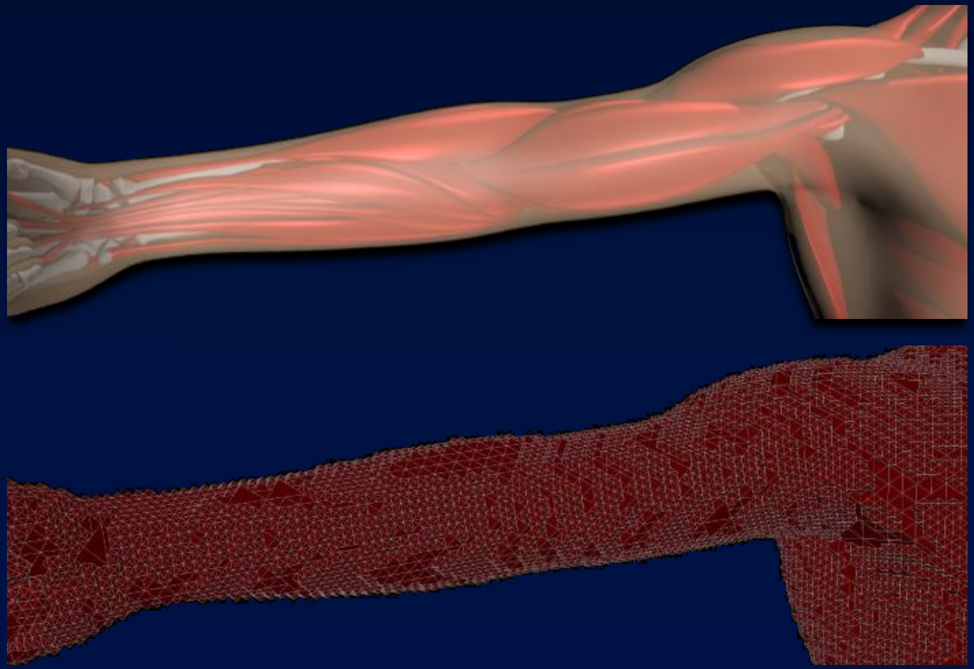
Tetrahedral lattice (7mm)

Cutting (3.8 million tets)

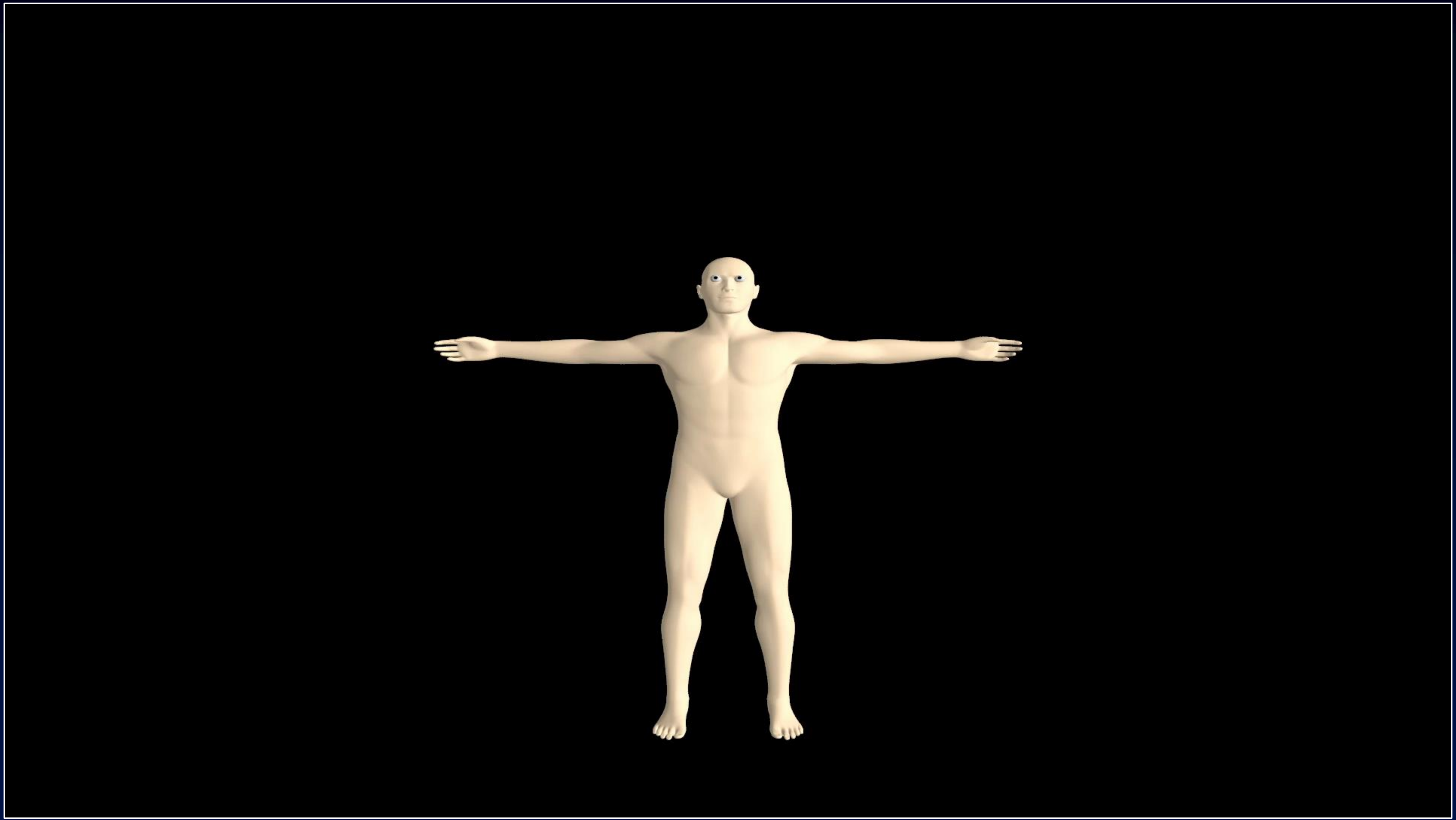
Coarsening (354K tets)

# Finite Element Soft Tissue Model

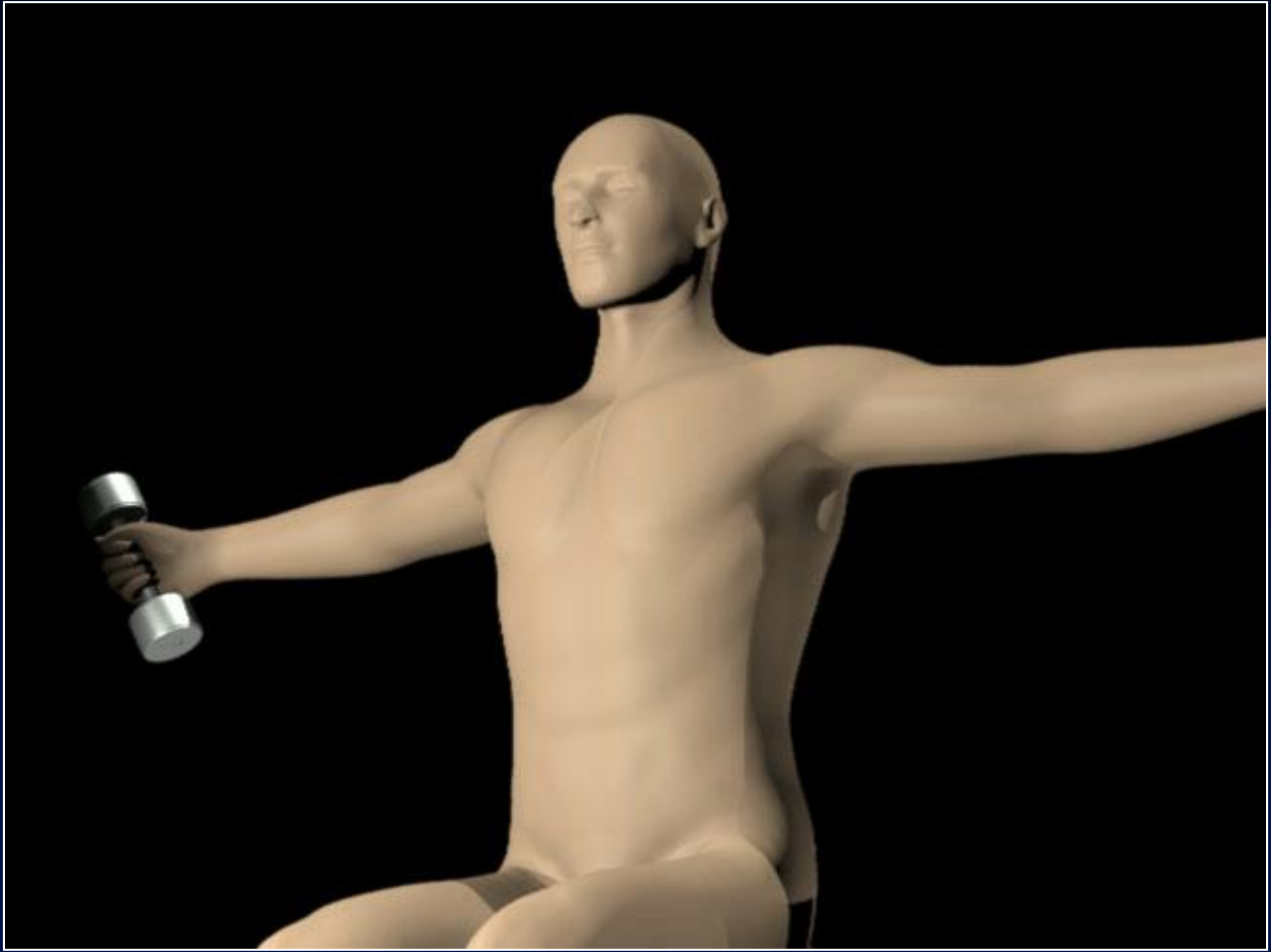
- Decoupling visualization geometry and simulation geometry
- 354K tetrahedral finite element simulation



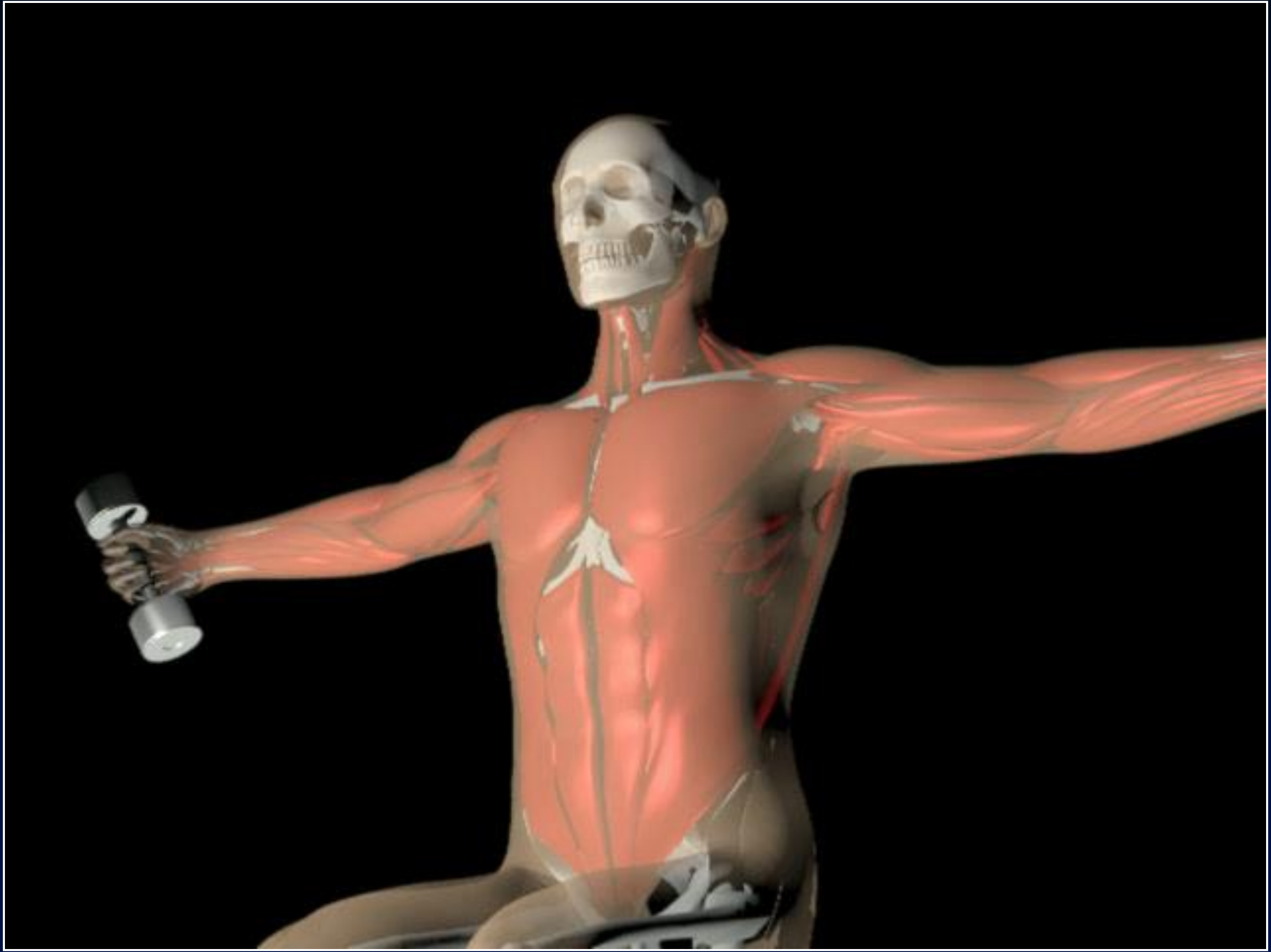
# The Biomechanical Human Musculoskeletal Model



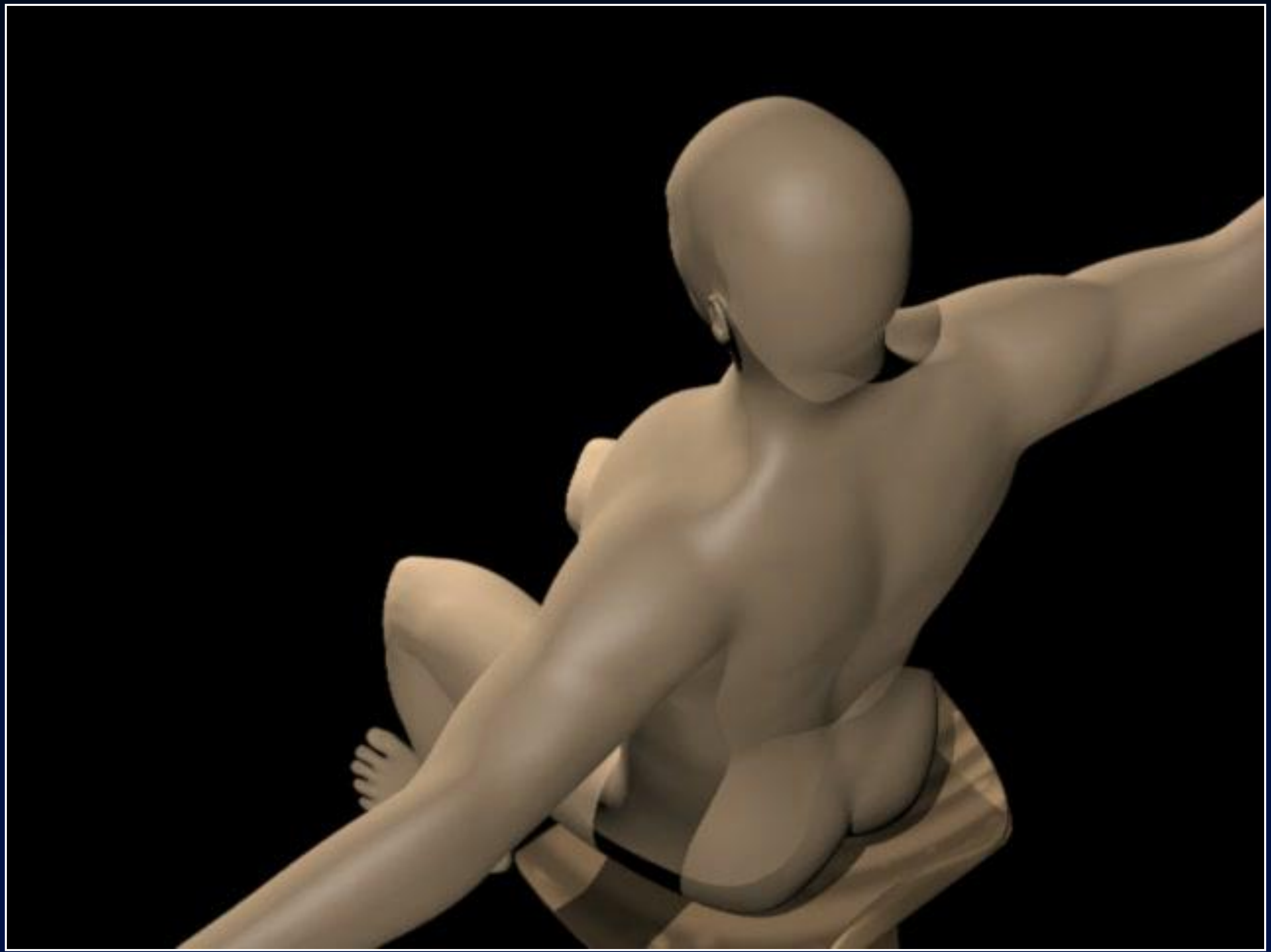
# Biomechanical Simulation With Inverse Dynamics Control



# Biomechanical Simulation
# With Inverse Dynamics Control



# Biomechanical Simulation With Inverse Dynamics Control



# Stiffness Control

## *Co-activation of opposing muscles*

Zero co-contraction High co-contraction

# Realistic Animation of Swimming

*Biomechanical human model immersed in simulated fluid*

# Realistic Simulation & Control of Human Swimming

## *Comprehensive biomechanical body model*

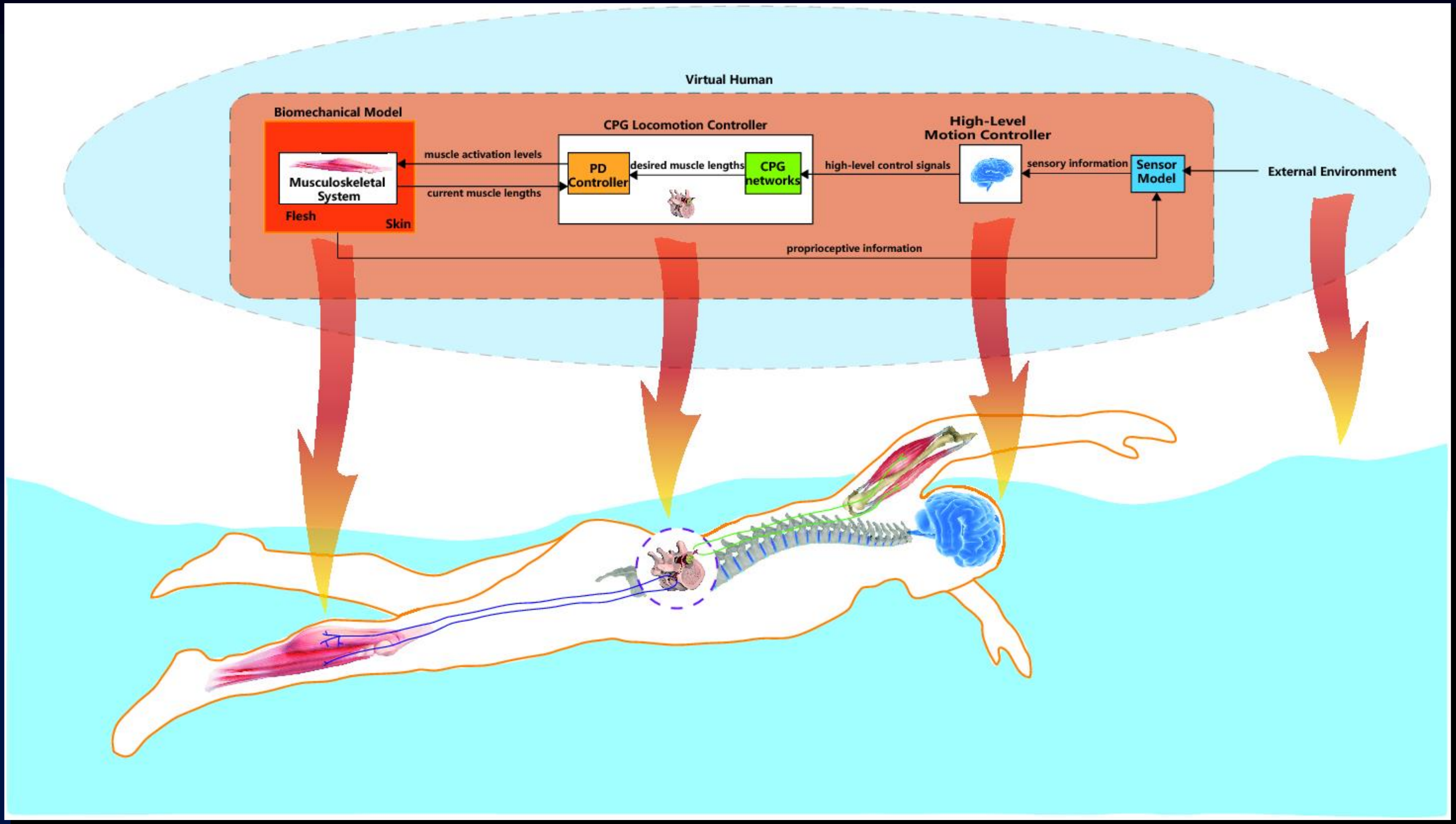
- Almost all the articular bones and skeletal muscles
  - *75 bones (165 DOFs), 846 muscles*
- Volumetric soft tissue model
  - *354K tetrahedral finite elements*

## *In a Navier-Stokes simulated fluid*

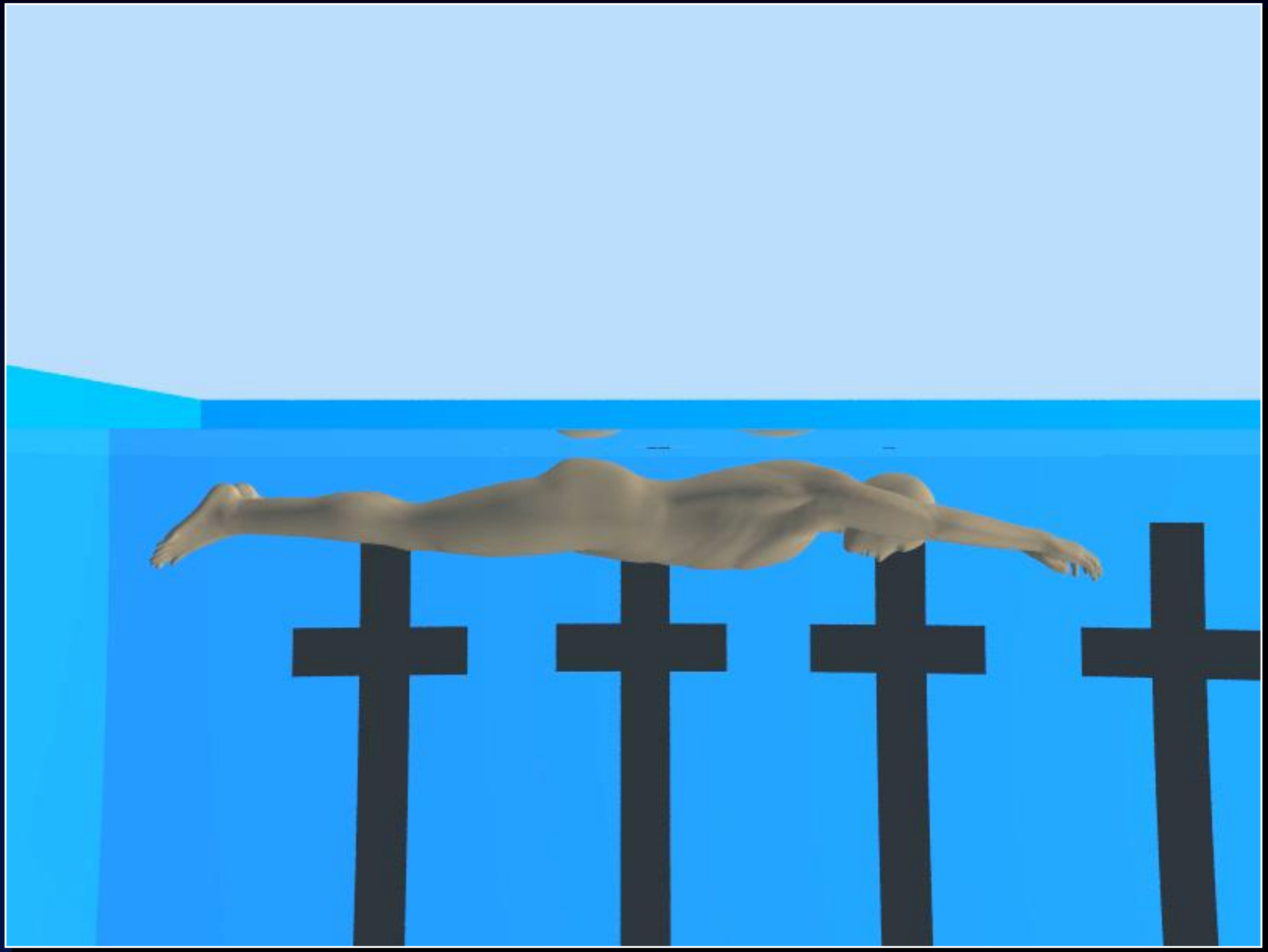
## *Biomimetic muscle actuator control*

- Central Pattern Generator (CPG) muscle control to generate multiple swimming modes

# The Virtual Human Swimmer

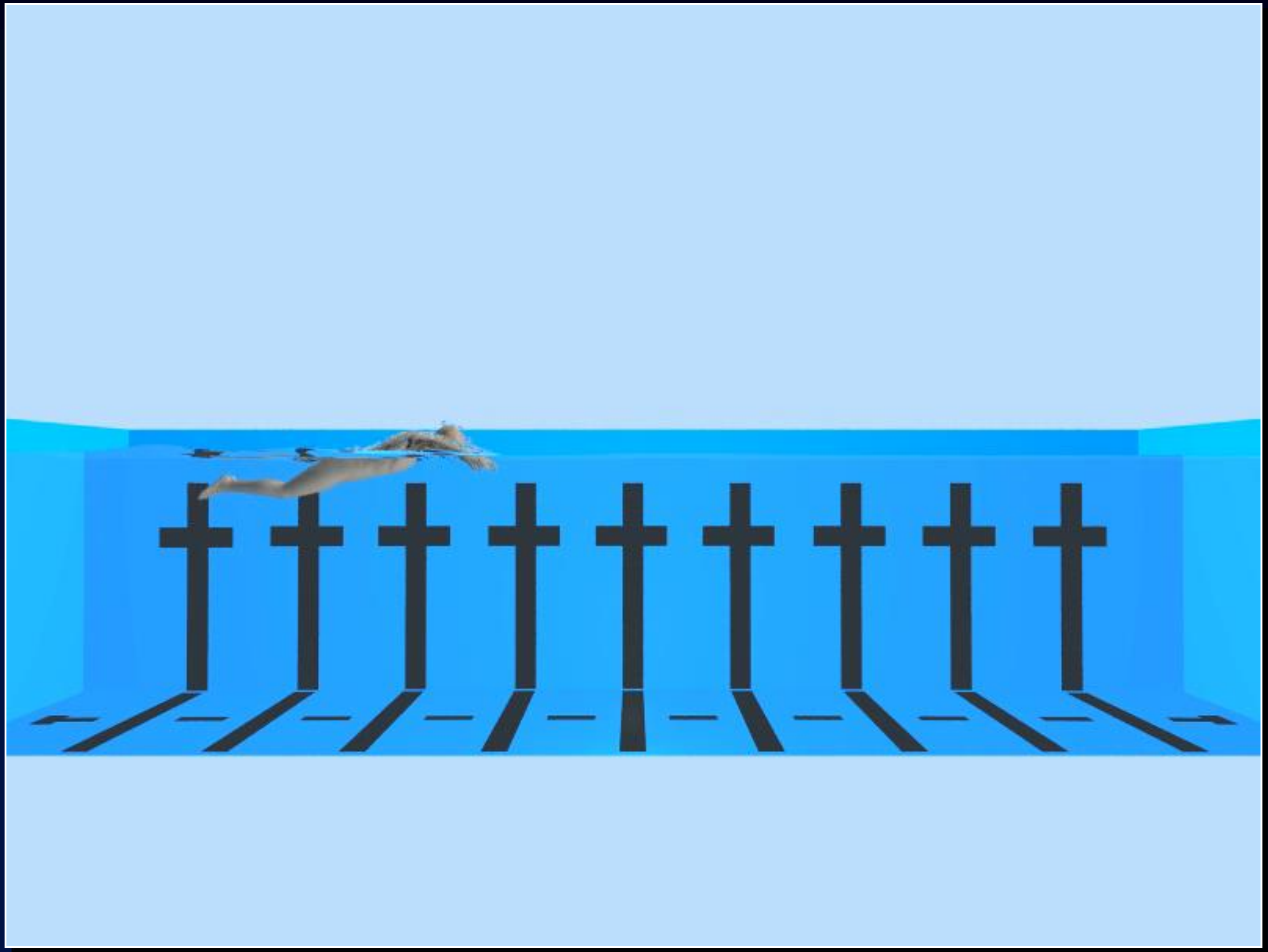


# Close-up View of the Biomechanical Swimmer Model



# Swimming Comparison

# Speed and Style Transitions



# Multi-Physics Simulation

## *Force-coupled, interleaved time-integration across three specialized simulators*

- Rigid/articulated body simulation — bones/skeleton
  - *Articulated multi-body method*
- Deformable solid body simulation — flesh
  - *Lagrangian finite element quasi-incompressible elasticity*
- Fluid simulation — water
  - *Eulerian fluid simulation with particle level-set method*

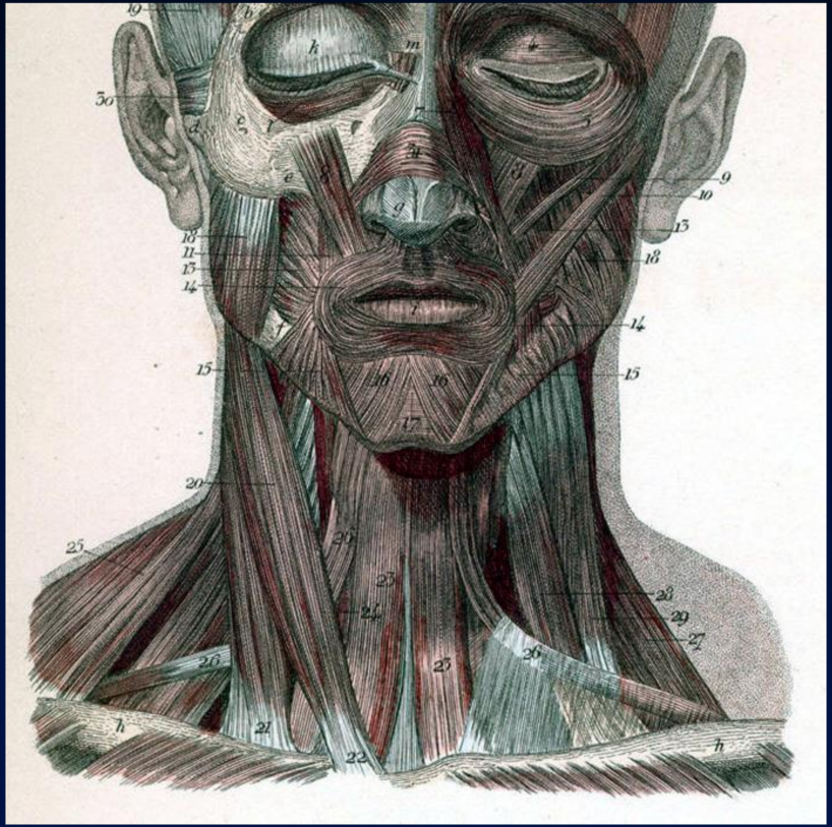
# Layered Simulation Components

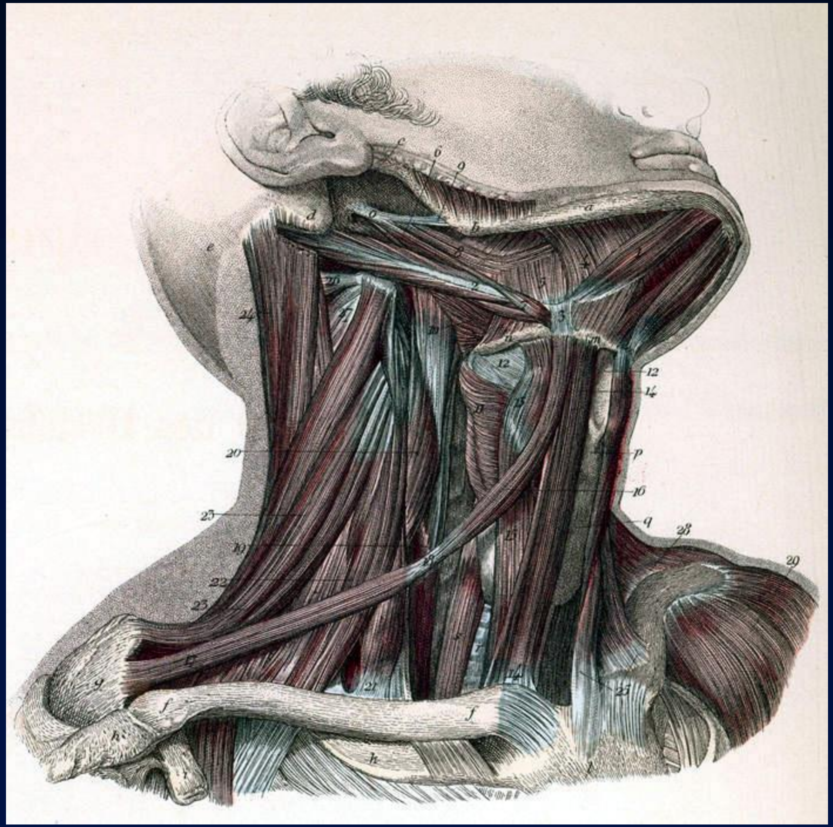
# Non-Locomotional, Task-Oriented Musculoskeletal Control

***The principled and only viable approach is learning-based neuromuscular control***

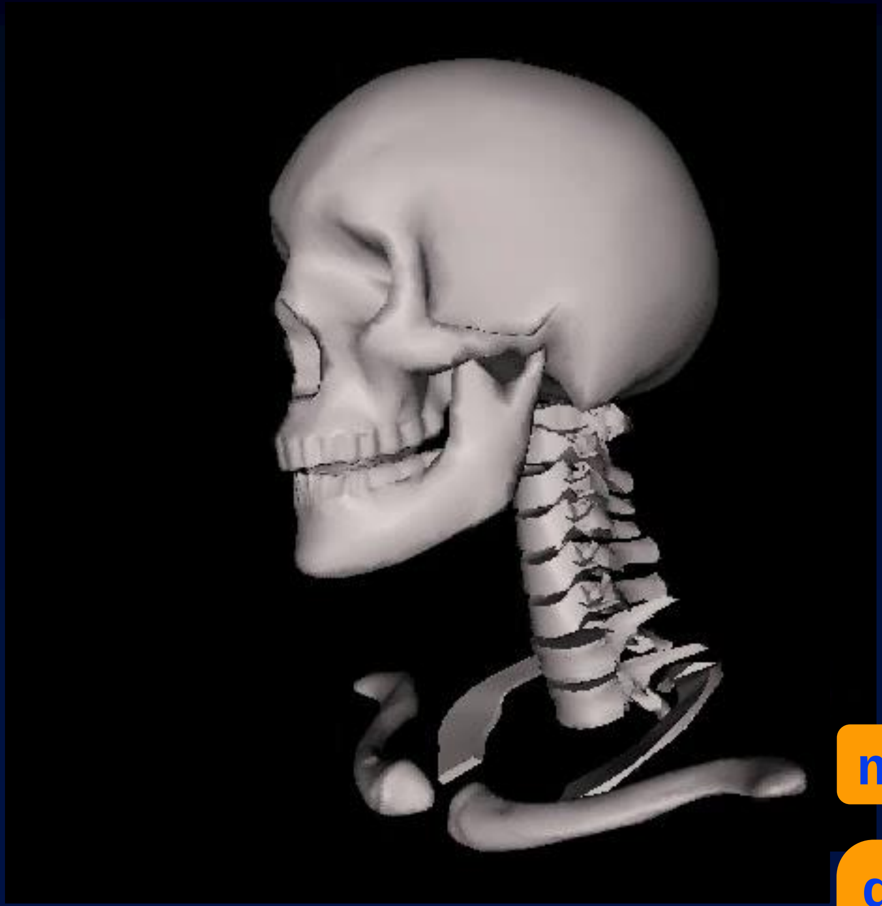
- Similar to how the human brain does it
- Let's first consider the cervicocephalic neuromuscular complex
  - *i.e., the muscles and bones of the neck/head subsystem*

# Anatomical Structure of the Neck





# Skeletal Model



- 7 cervical vertebrae and a skull coupled by 3-DOF joints
- Ligaments/disks→ passive joint springs
- Equations of motion

$$M(\mathbf{q})\ddot{q} + b(q,\dot{q}) = B(q)f_c(q,\dot{q},a)$$

mass

gravity, Coriolis, passive elastic forces

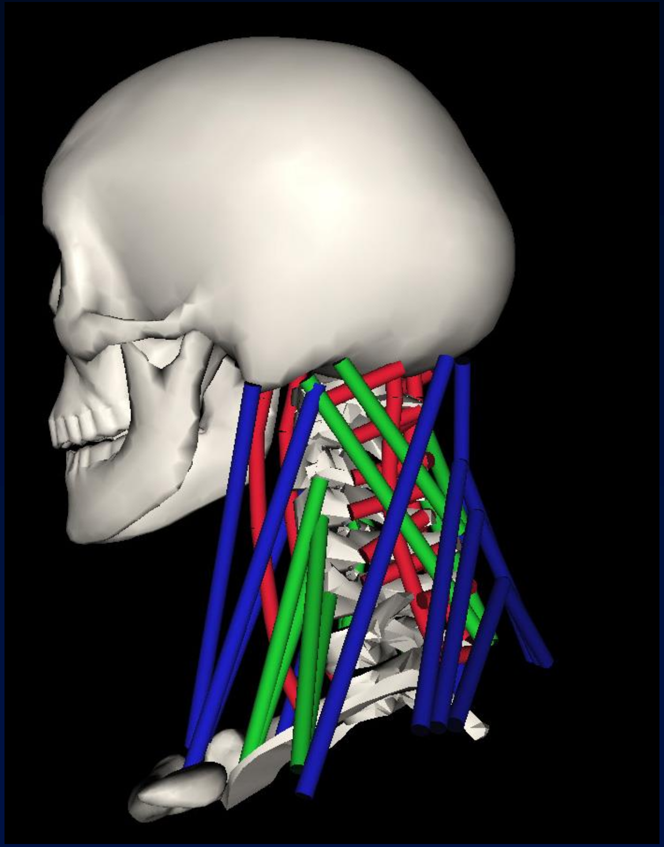
moment arm matrix

active muscle force

neural input

# Biomechanical Neck Model

[Lee, Terzopoulos 2006]



Total of 72 anatomically-based muscle actuators in 3 layers

48 *deep* muscles
(16 longus colli, 16 erector, 16 rotator)

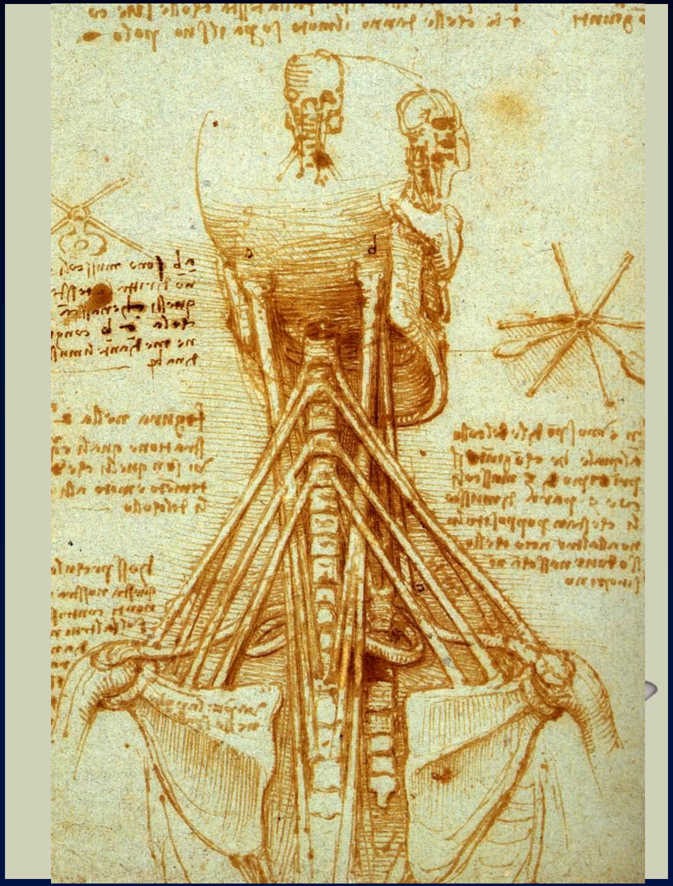
*6 muscles at each joint increase controllability*

12 *intermediate* muscles
(scalerius: 4 anterior, 4 posterior, 4 capitis)

12 *superficial* muscles
(2 sternomastoid, 2 cleidooccipital, 8 trapezius)

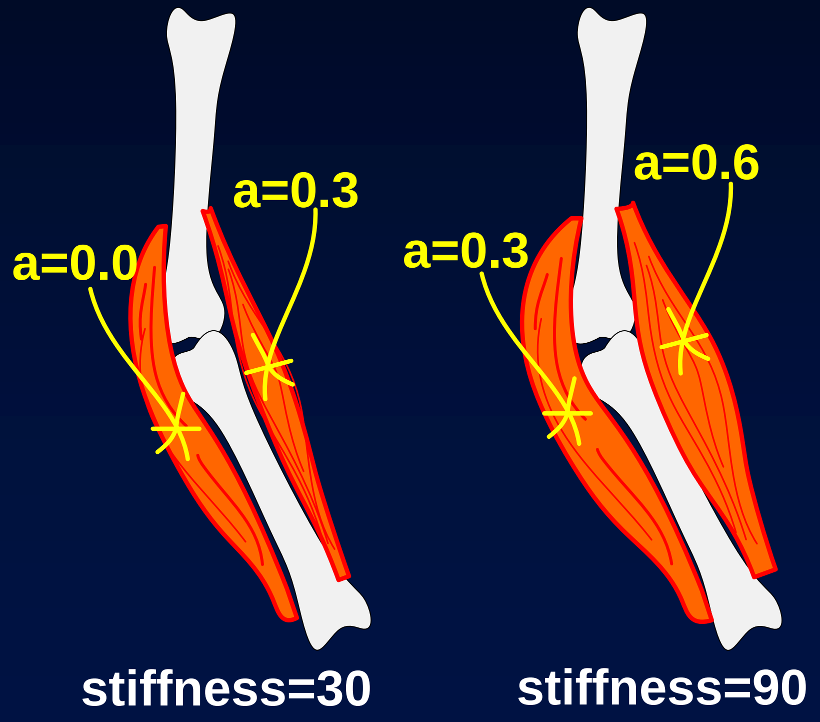
The challenge was co-actuation and control

# What Would Leonardo da Vinci Think of This?

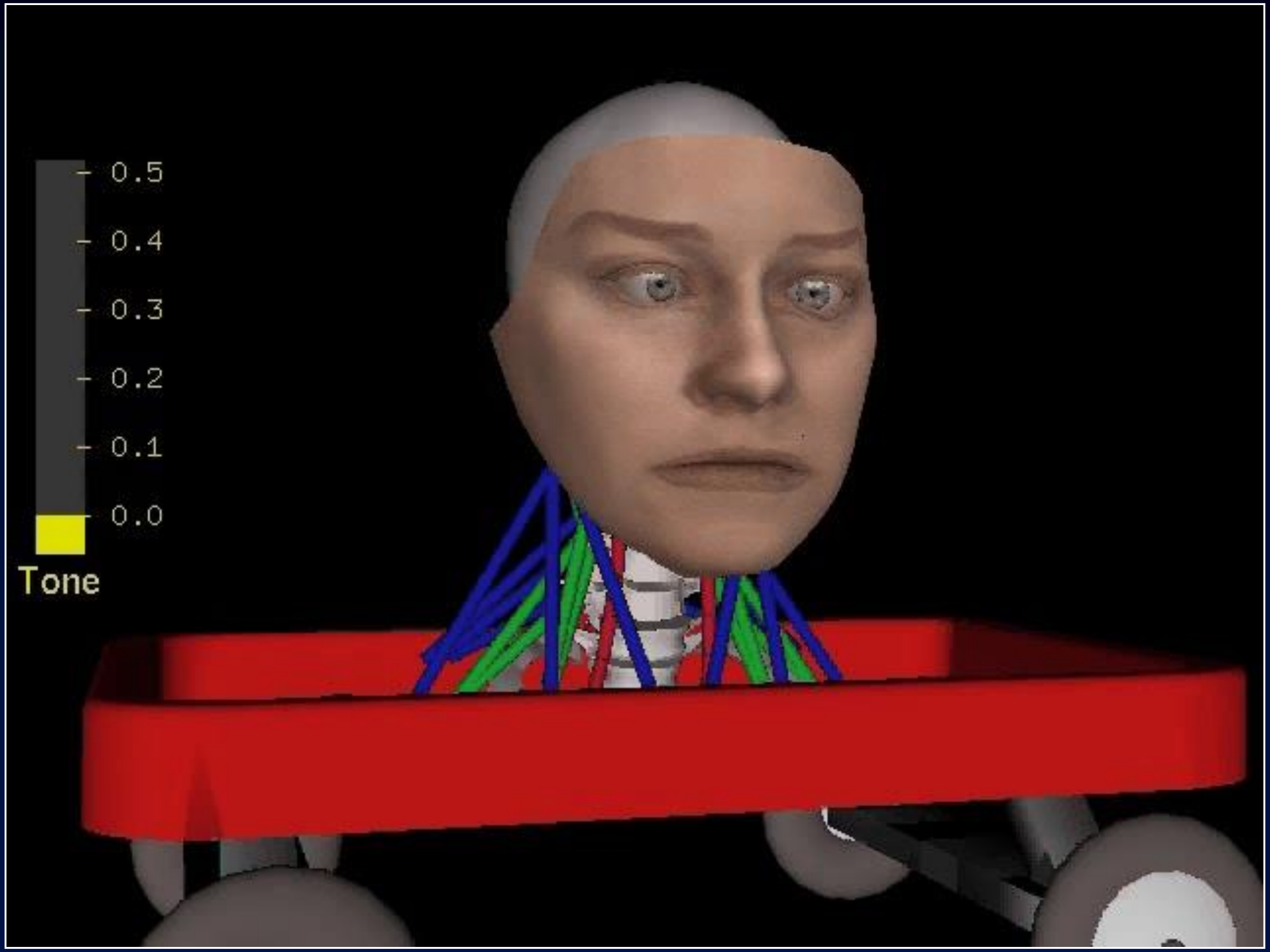


# Neck-Head-Face Animation

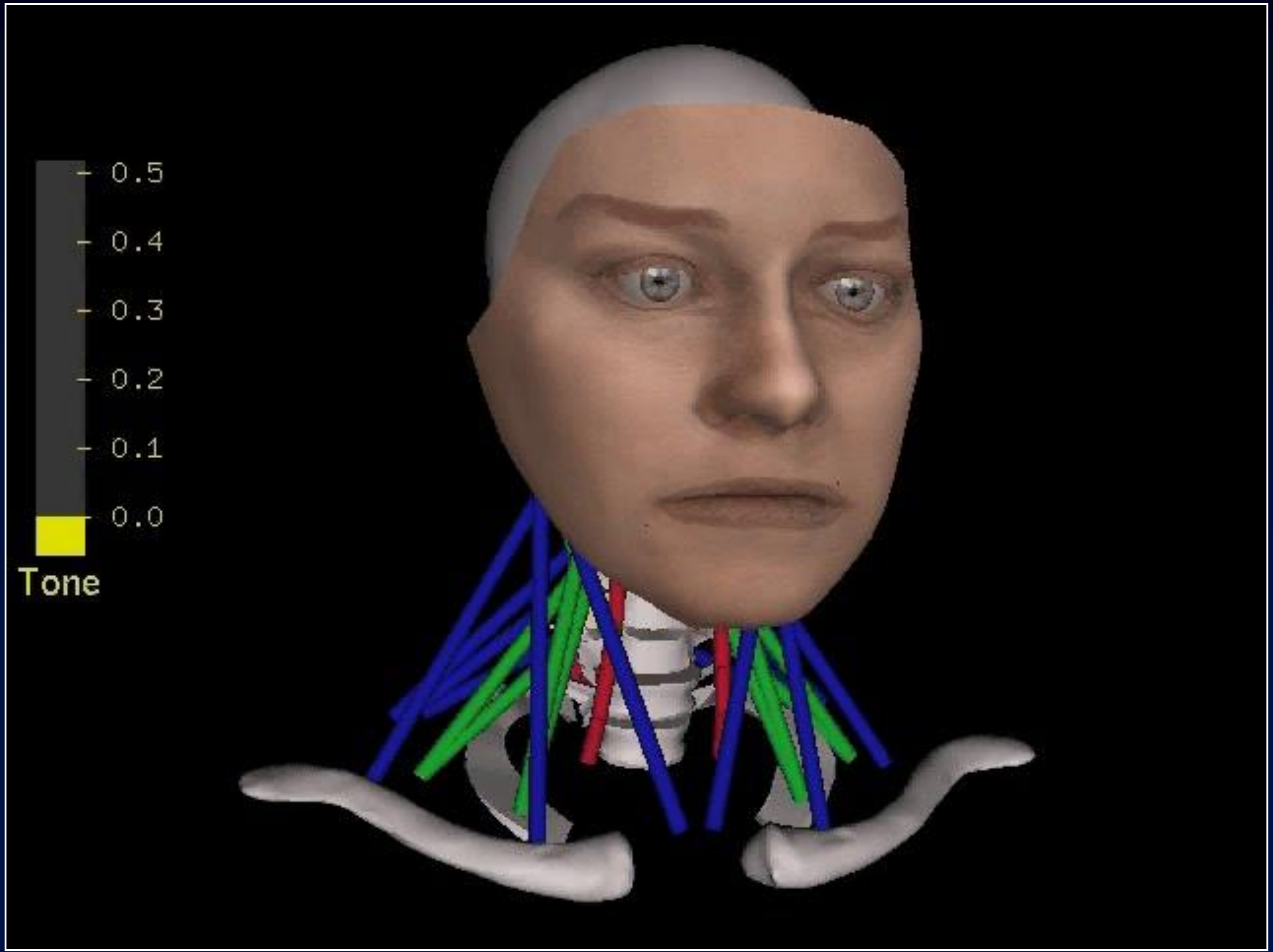
# Stiffness Control by Muscle Co-Contraction



# Stiffness Control

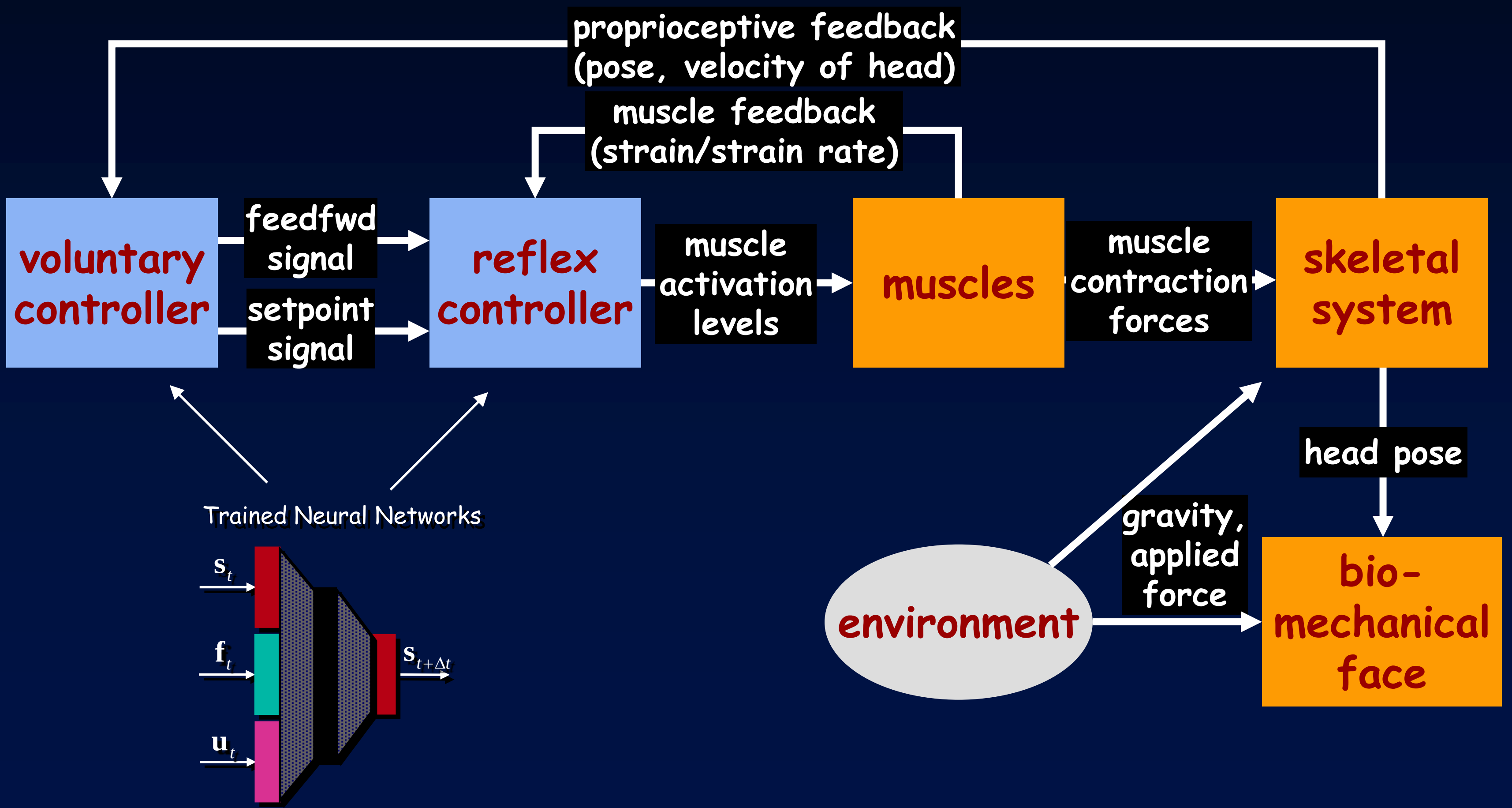


# Stiffness Control



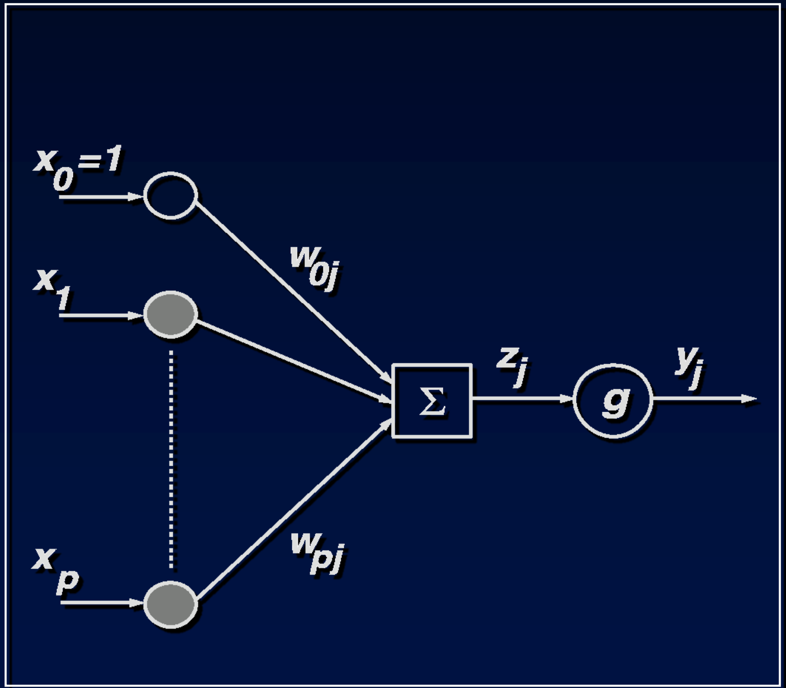
# Biomechanical Simulation of the Neck-Head-Face Complex

## Neuromusculoskeletal model

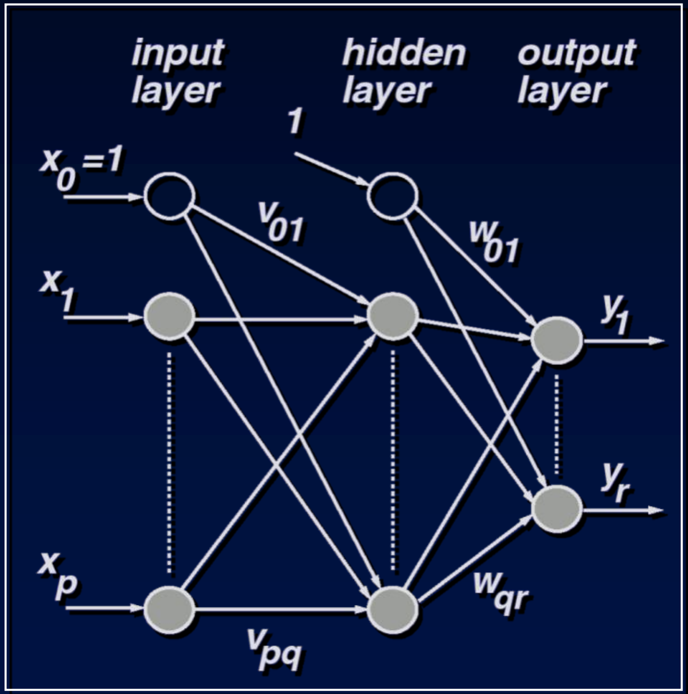


# (Shallow) Artificial Neural Networks

## Networks of simple computing elements



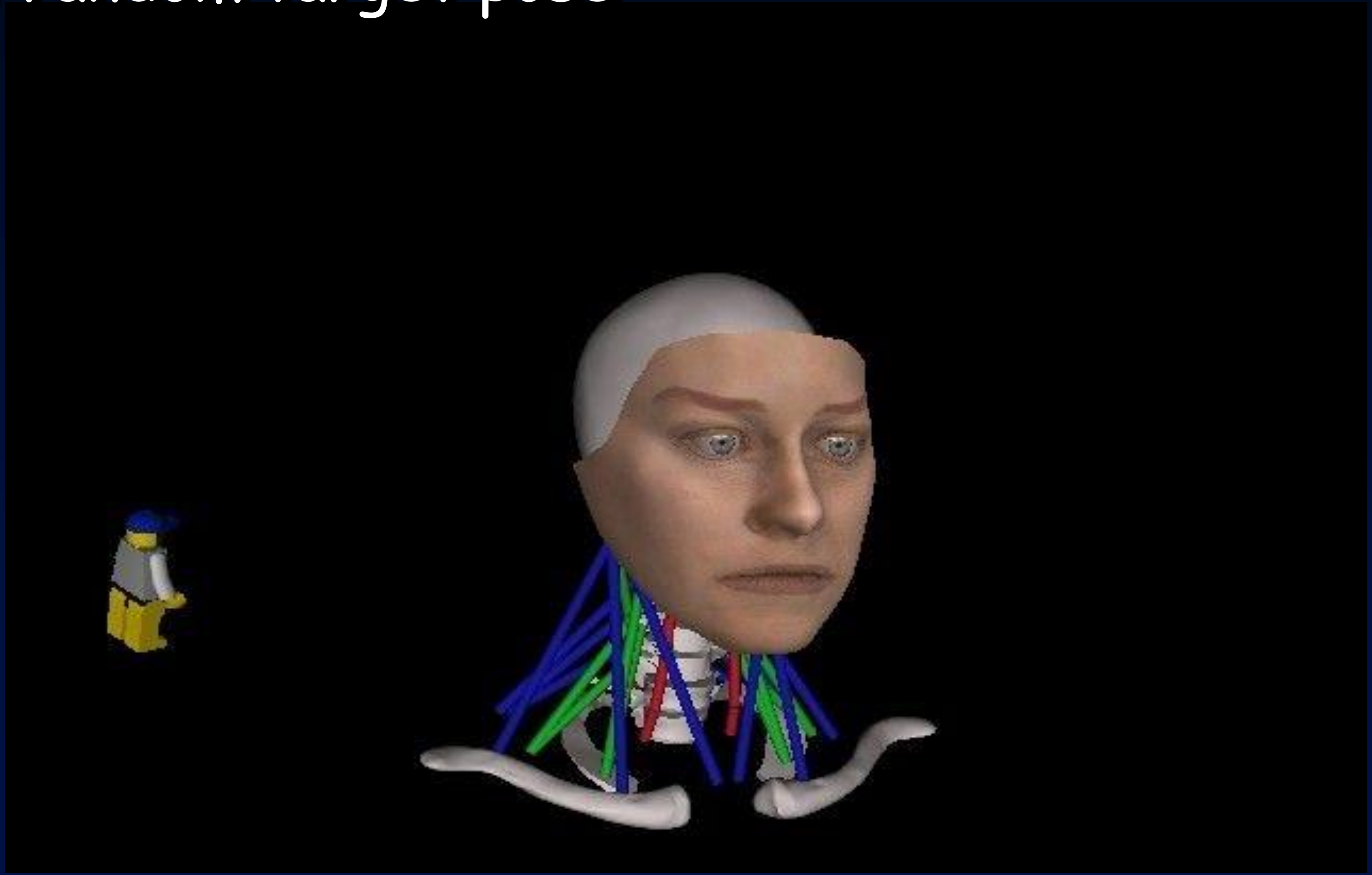

Neuron




Feedforward Network

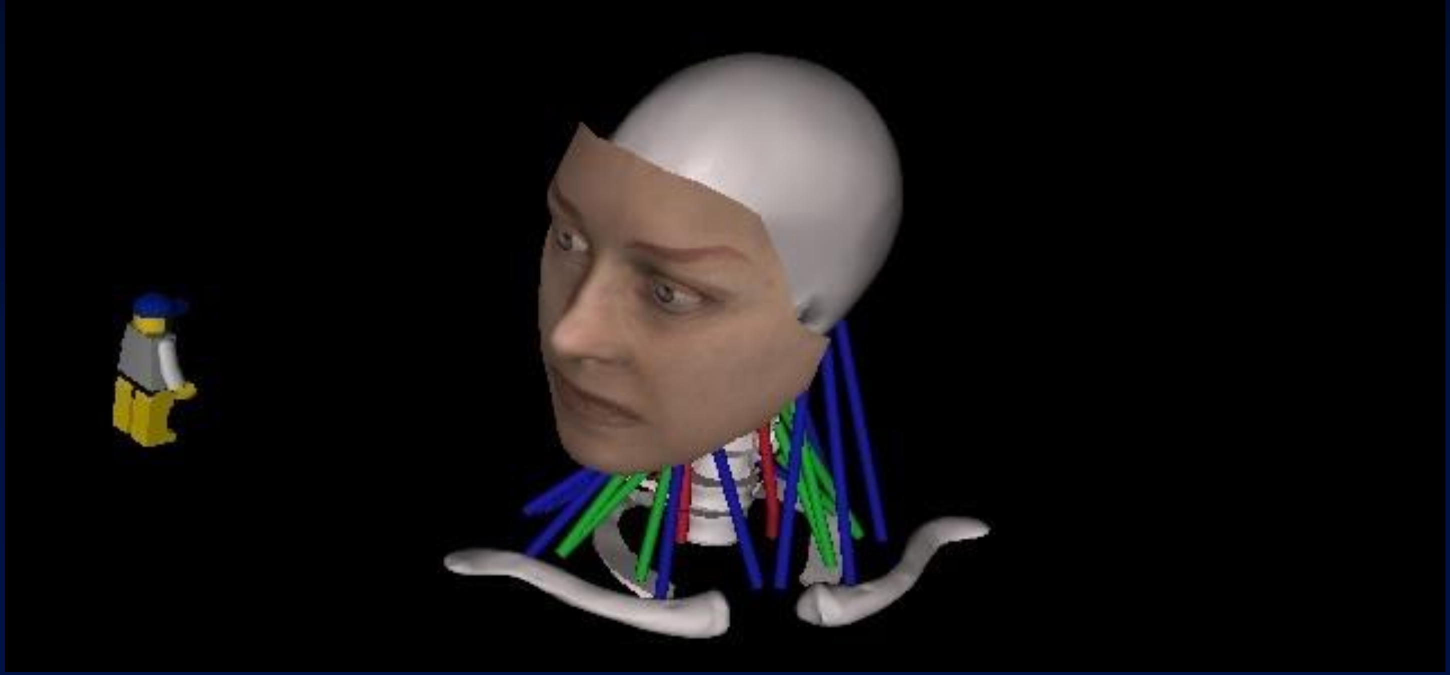
# Training the Neural Networks

- Set random target pose



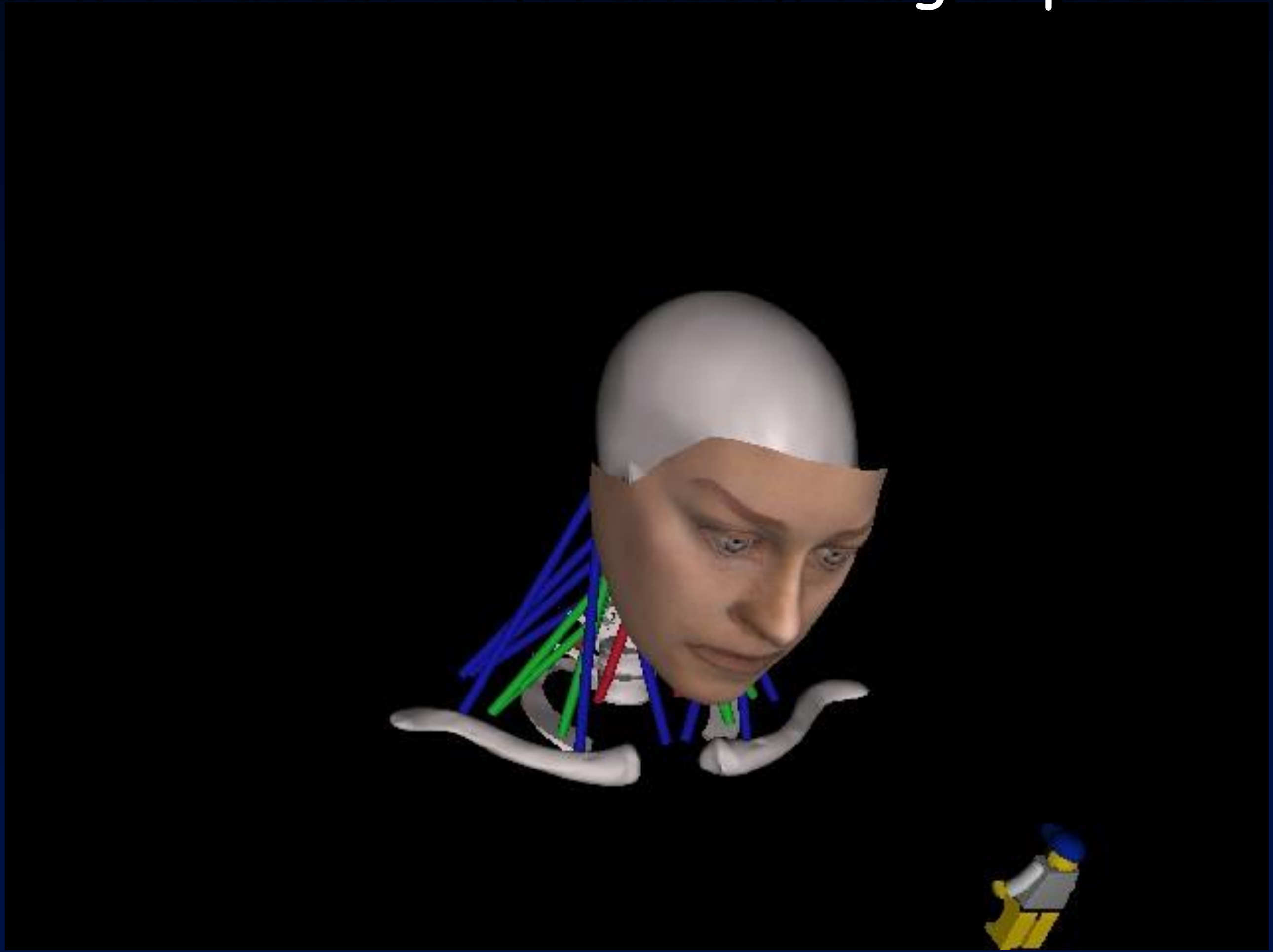
# Training the Neural Networks

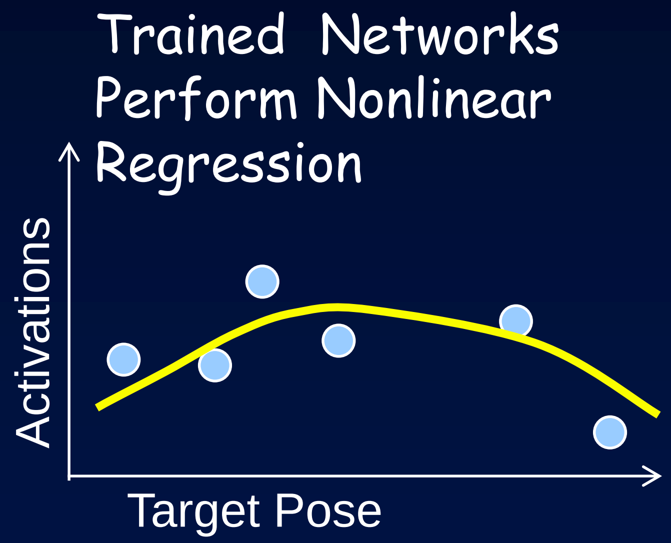
- Using inverse kinematics, compute desired joint angles
- Using inverse dynamics, compute muscle activations to achieve desired joint angles (under gravity)



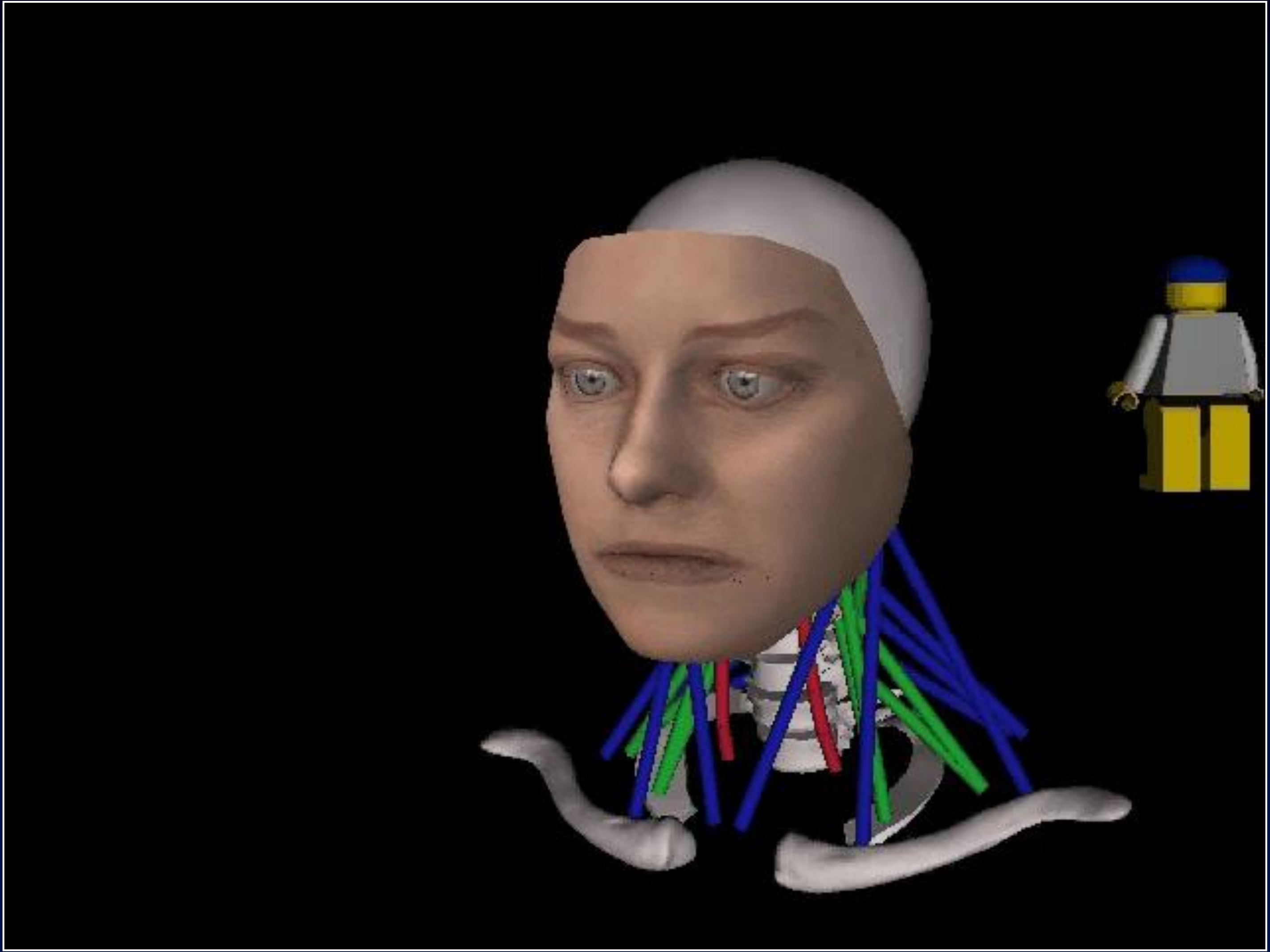
# Training the Neural Networks

- Repeat with about 20K random target poses

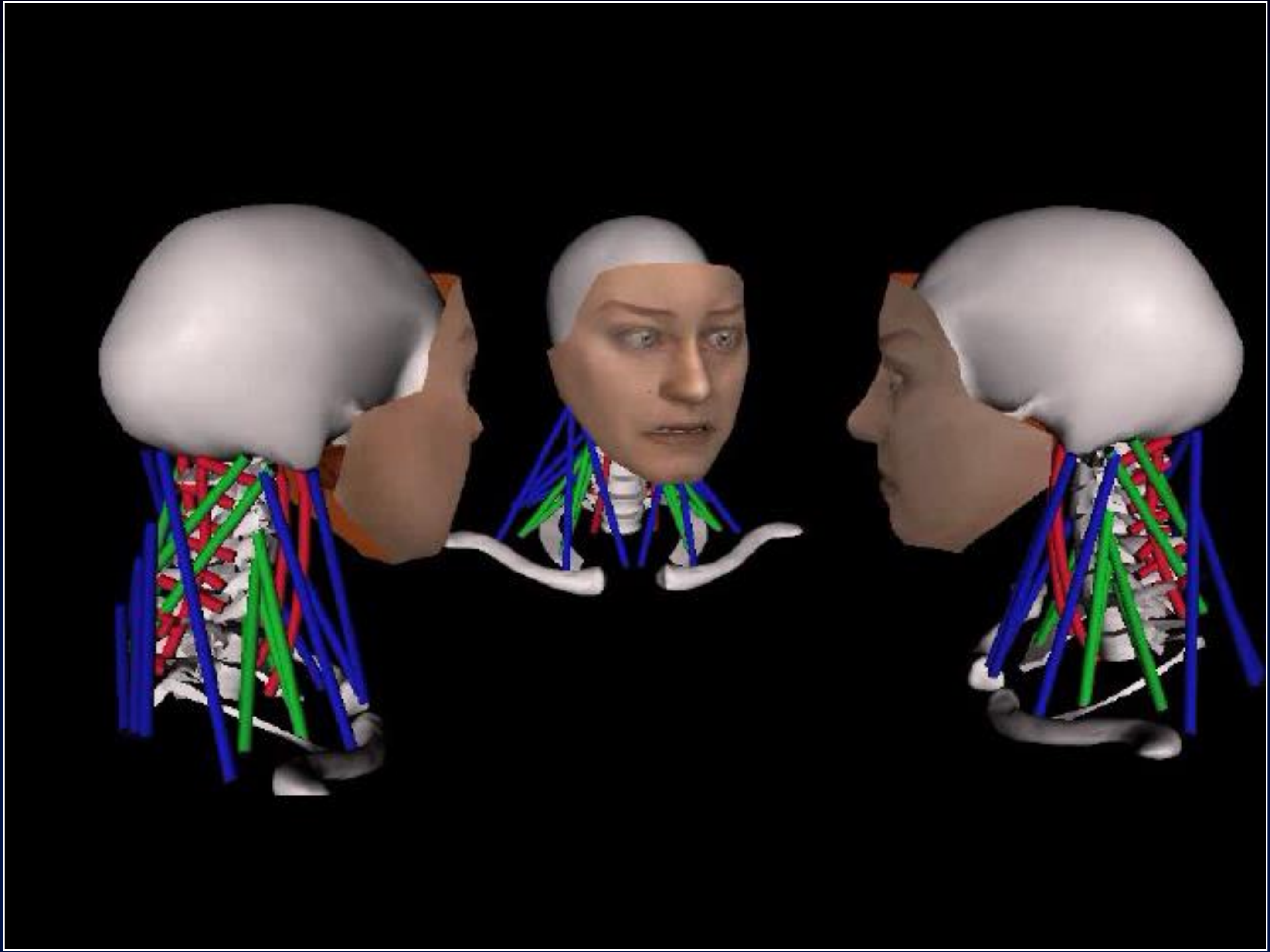




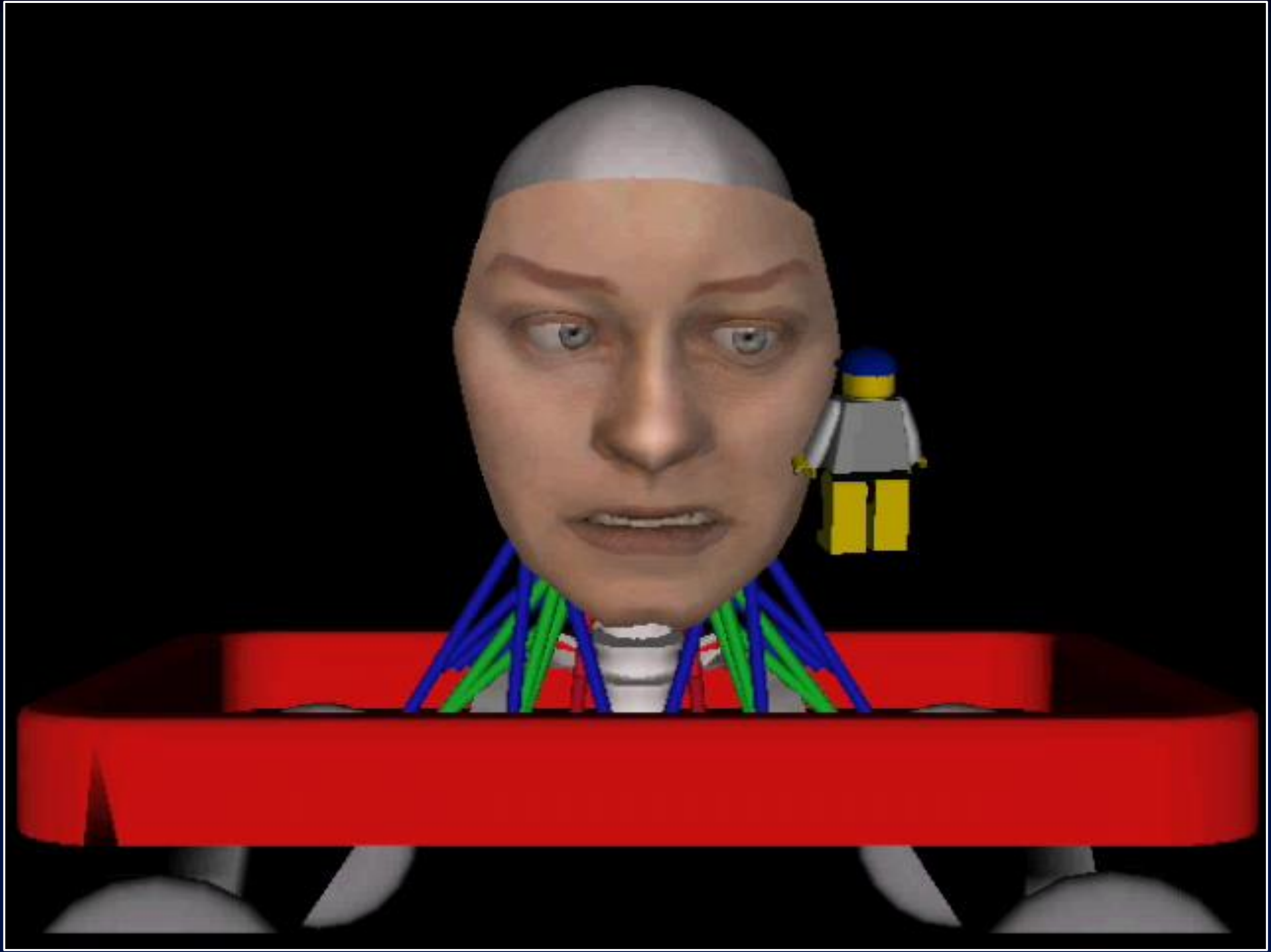
# Neck-Head-Face-Eye Behavior



# Autonomous Multi-Head Behavioral Interaction



# Varying Shoulder Orientation

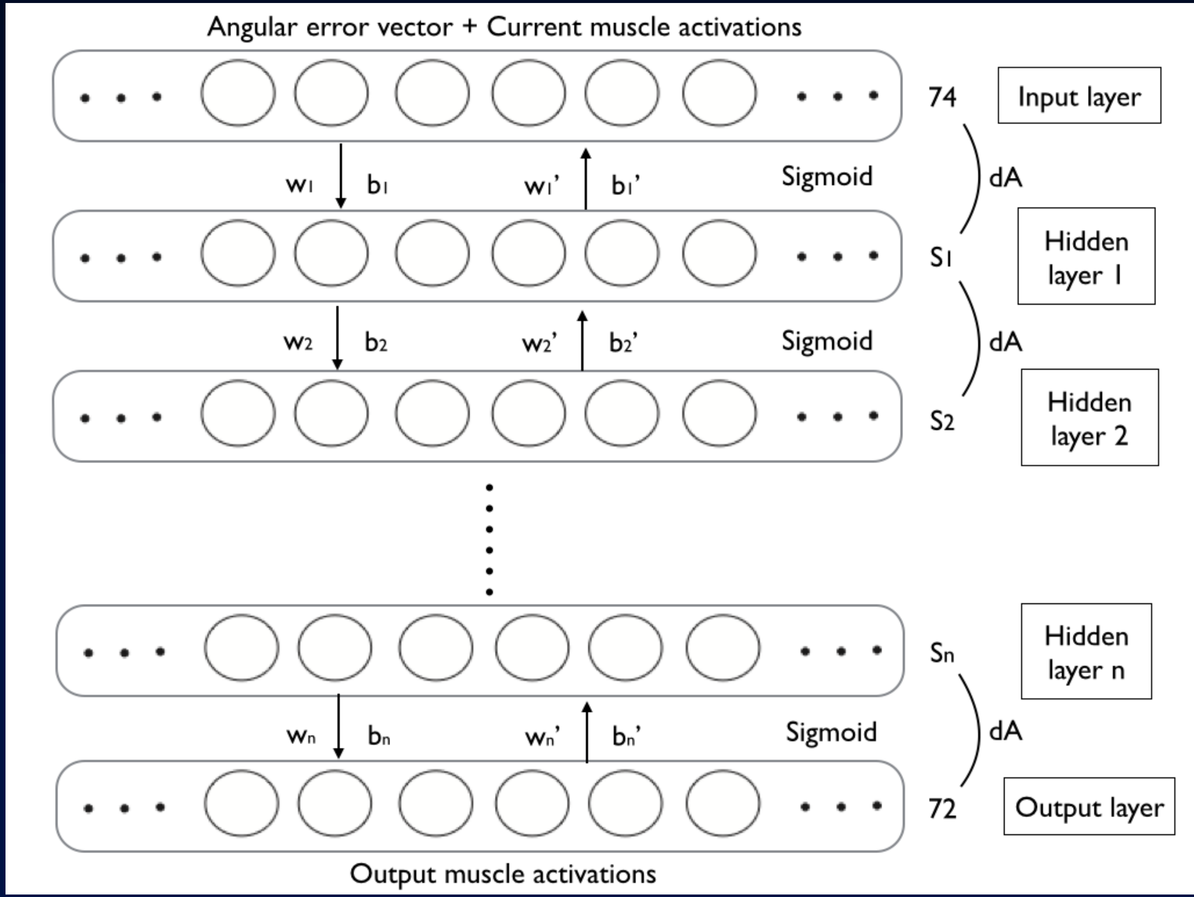


# Deep Learning of Neuromuscular Control

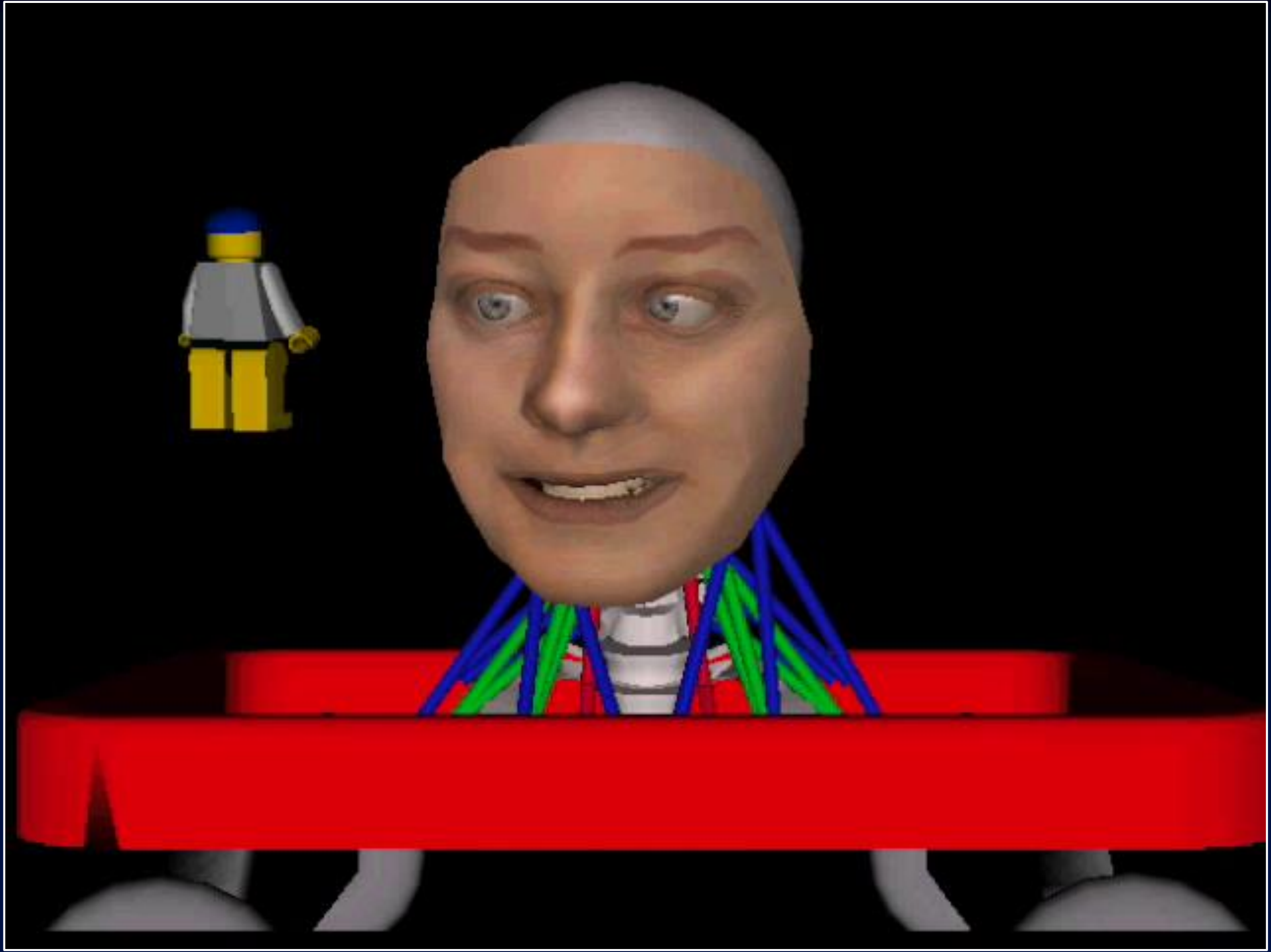
## *Neuromuscular controller architecture*

[Nakada, Terzopoulos 2015]

- Stacked autoencoders

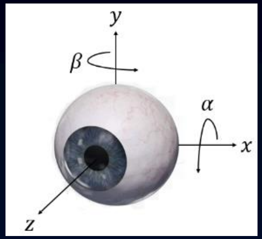


# Robust Deep Neuromuscular Control



# Deep Learning of Biomimetic Sensorimotor Control

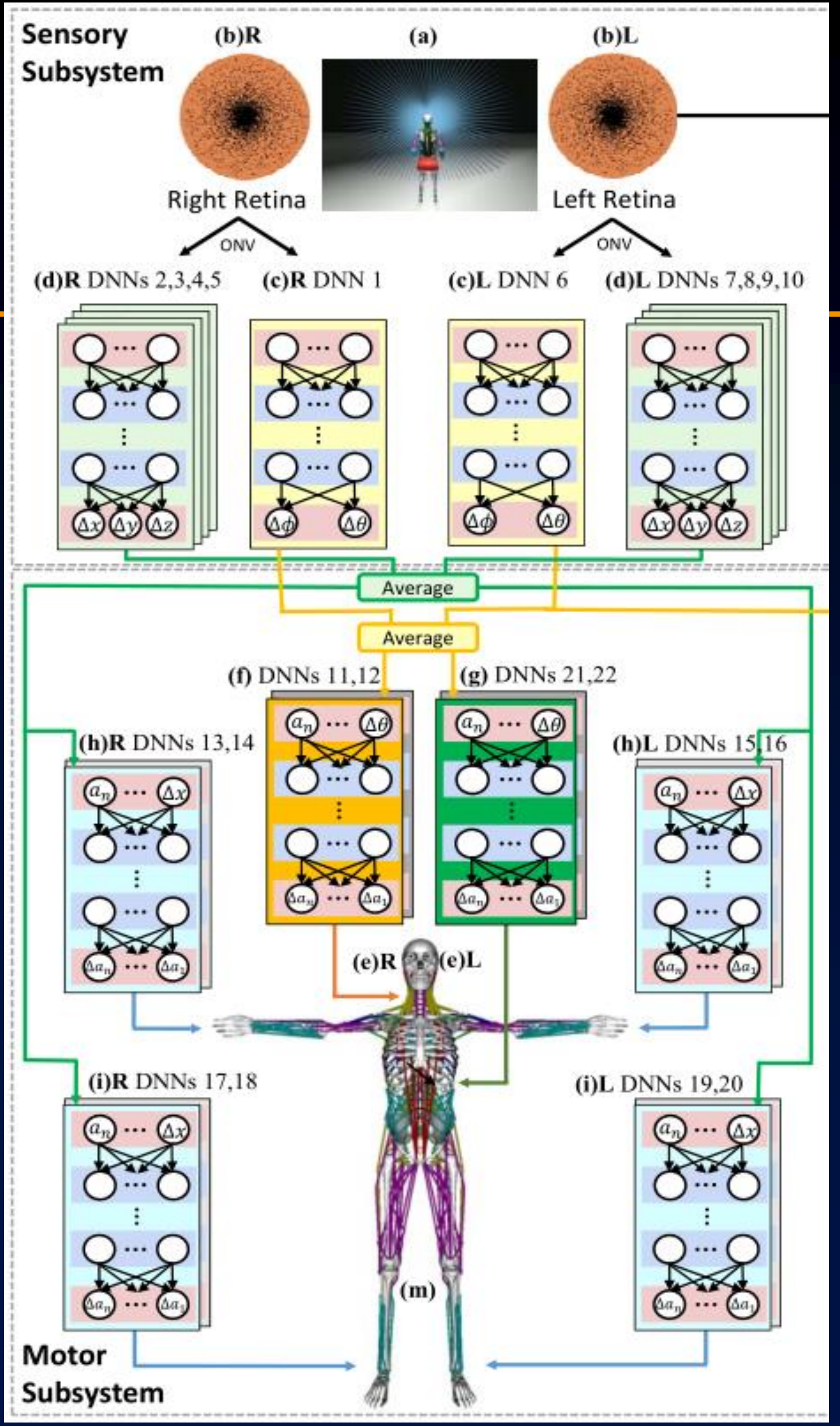
## *Perception subsystem*



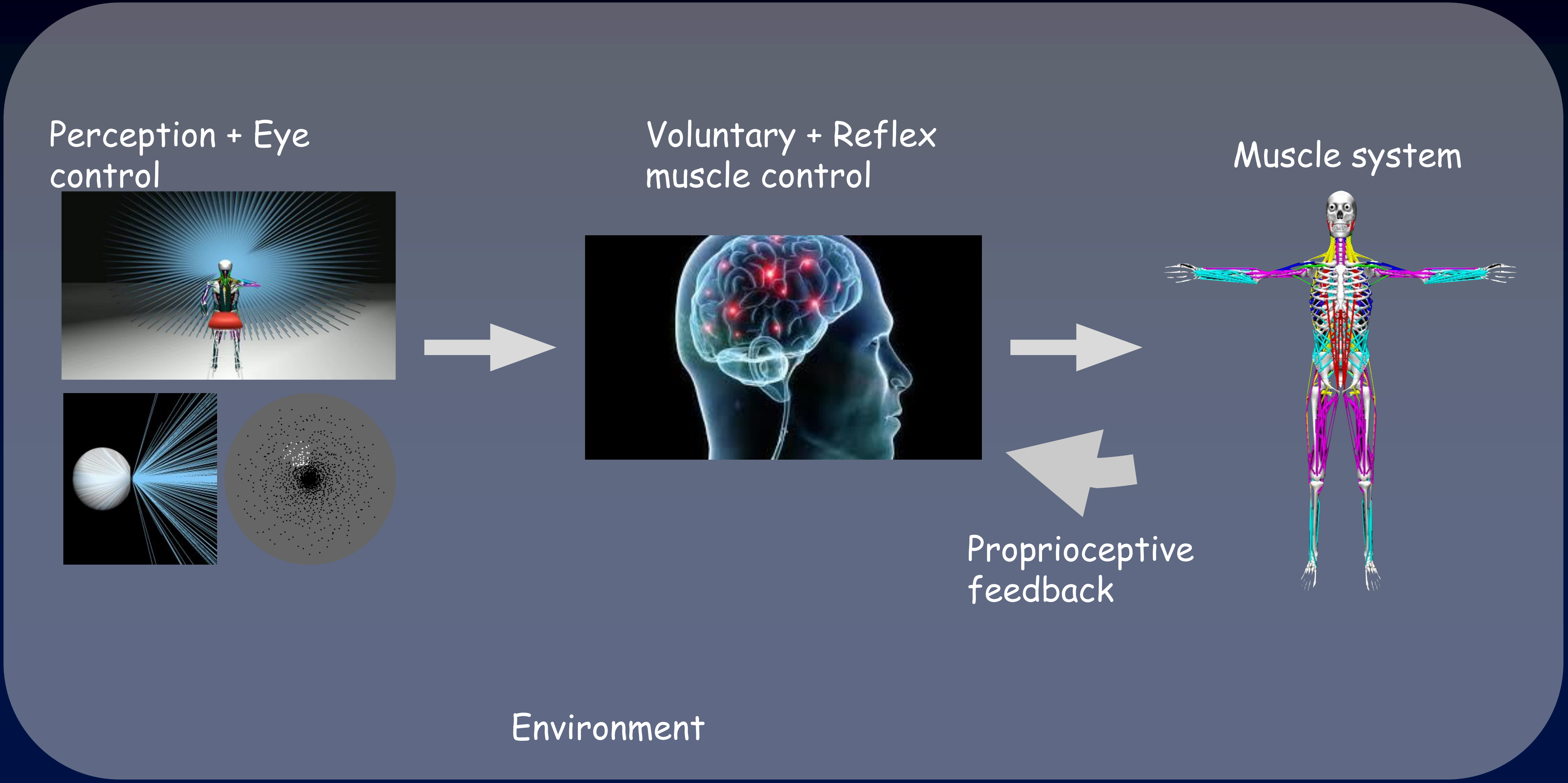

- Eyes capable of eye movements
- Retinas with foveated photoreceptor distributions
- Perception using **10** deep neural networks (DNNs)

## *Motor subsystem*

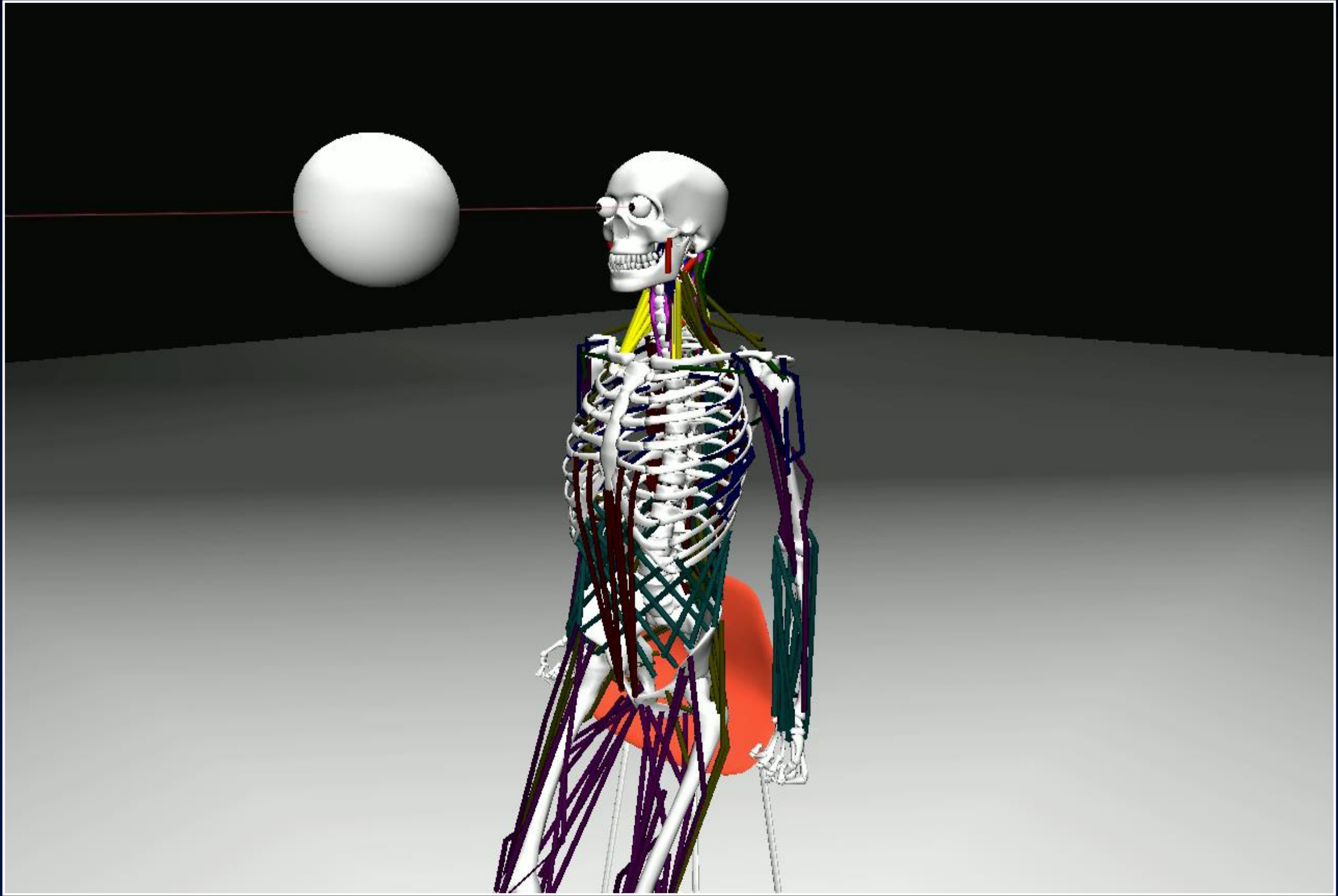
- **12** DNN neuromuscular controllers
  - *Ocular complex (6 extraocular muscles)*
  - *Cervicocephalic complex (216 neck muscles)*
  - *Torso complex (443 muscles)*
  - *4 limbs (arms: 29 muscles - legs: 39 muscles)*



# System Overview

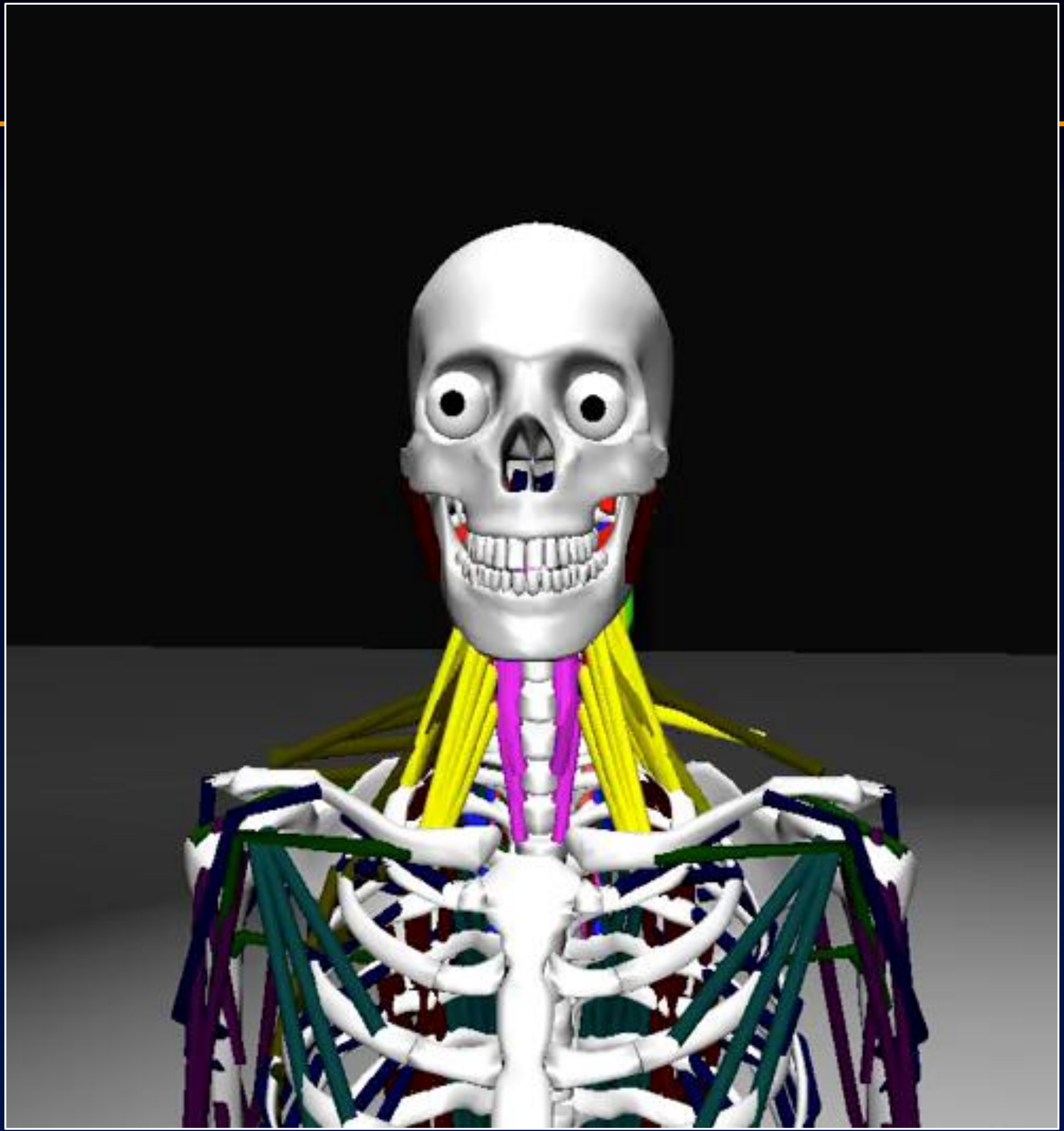


# Muscle-Actuated Dynamic Control

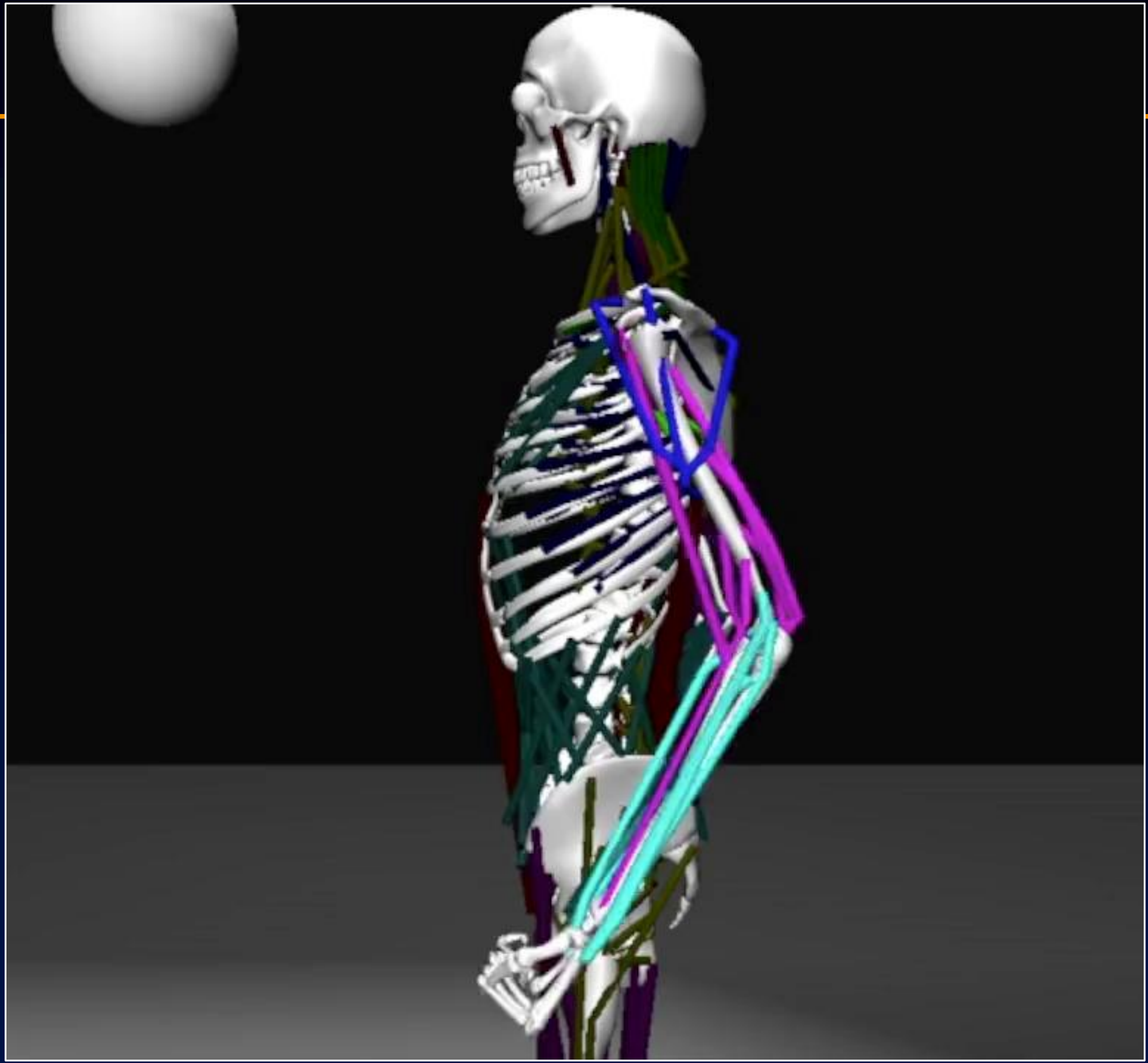


[Nakada, Zhou, Weiss, Terzopoulos 2018]

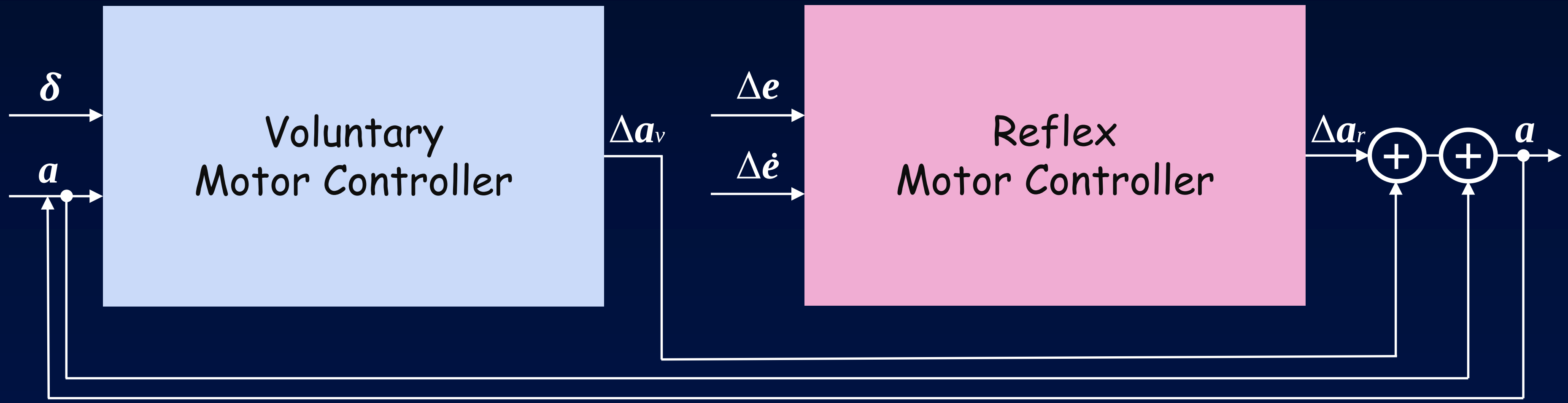
## Reactivate muscles



## Reactivate muscles

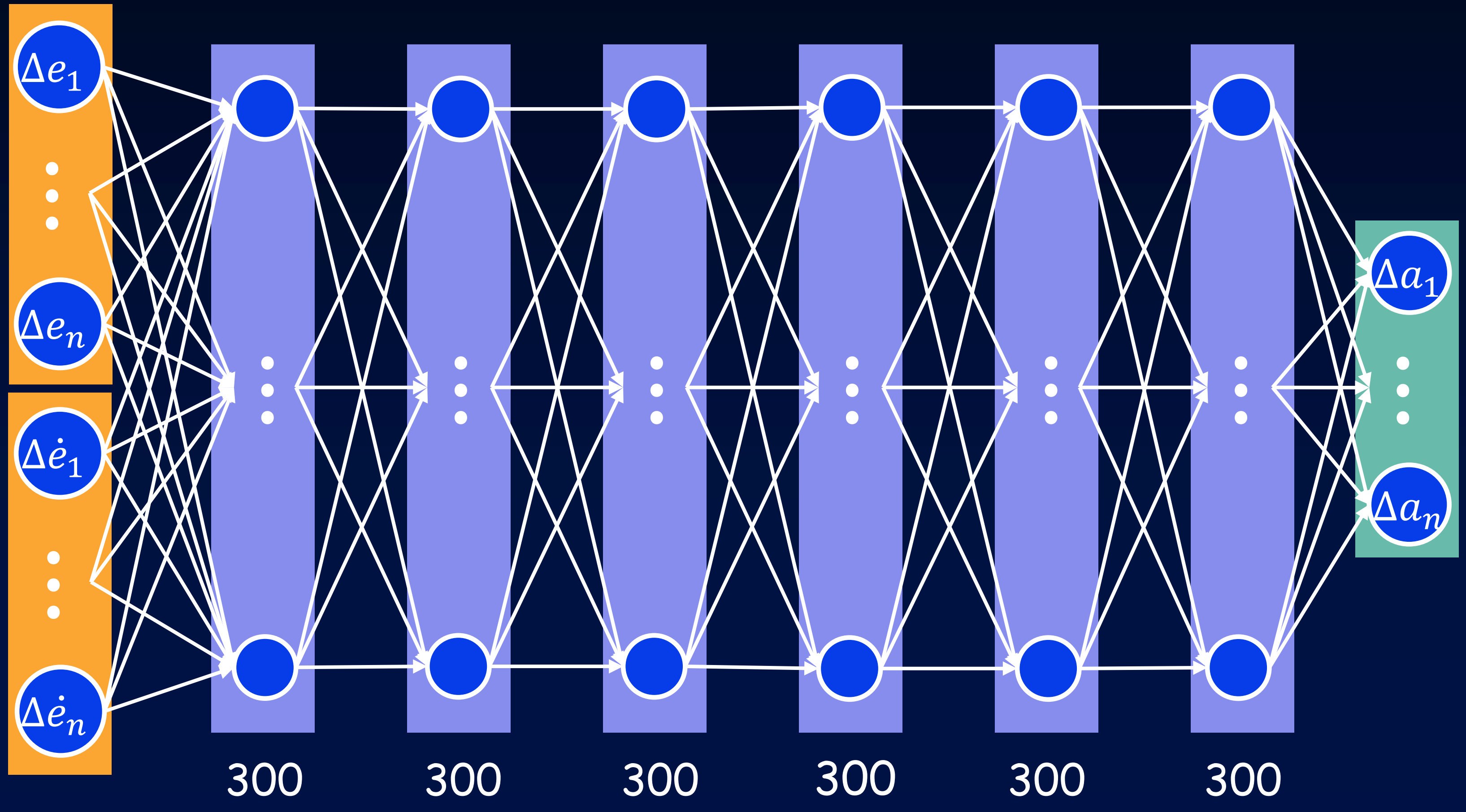


# Neuromuscular Motor Controller Architecture



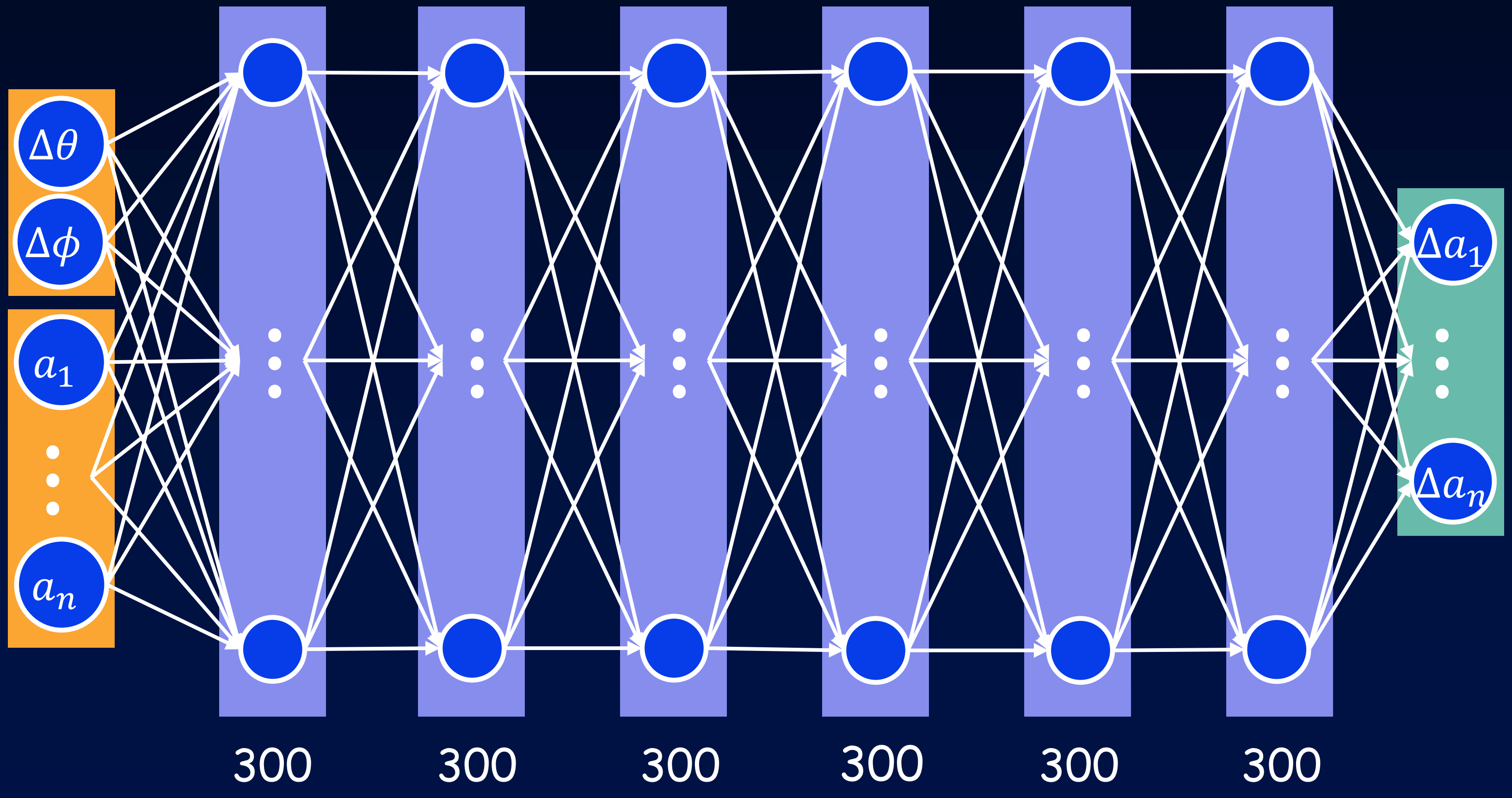
# Reflex Controller DNNs

## *Fully-connected DNN architecture*



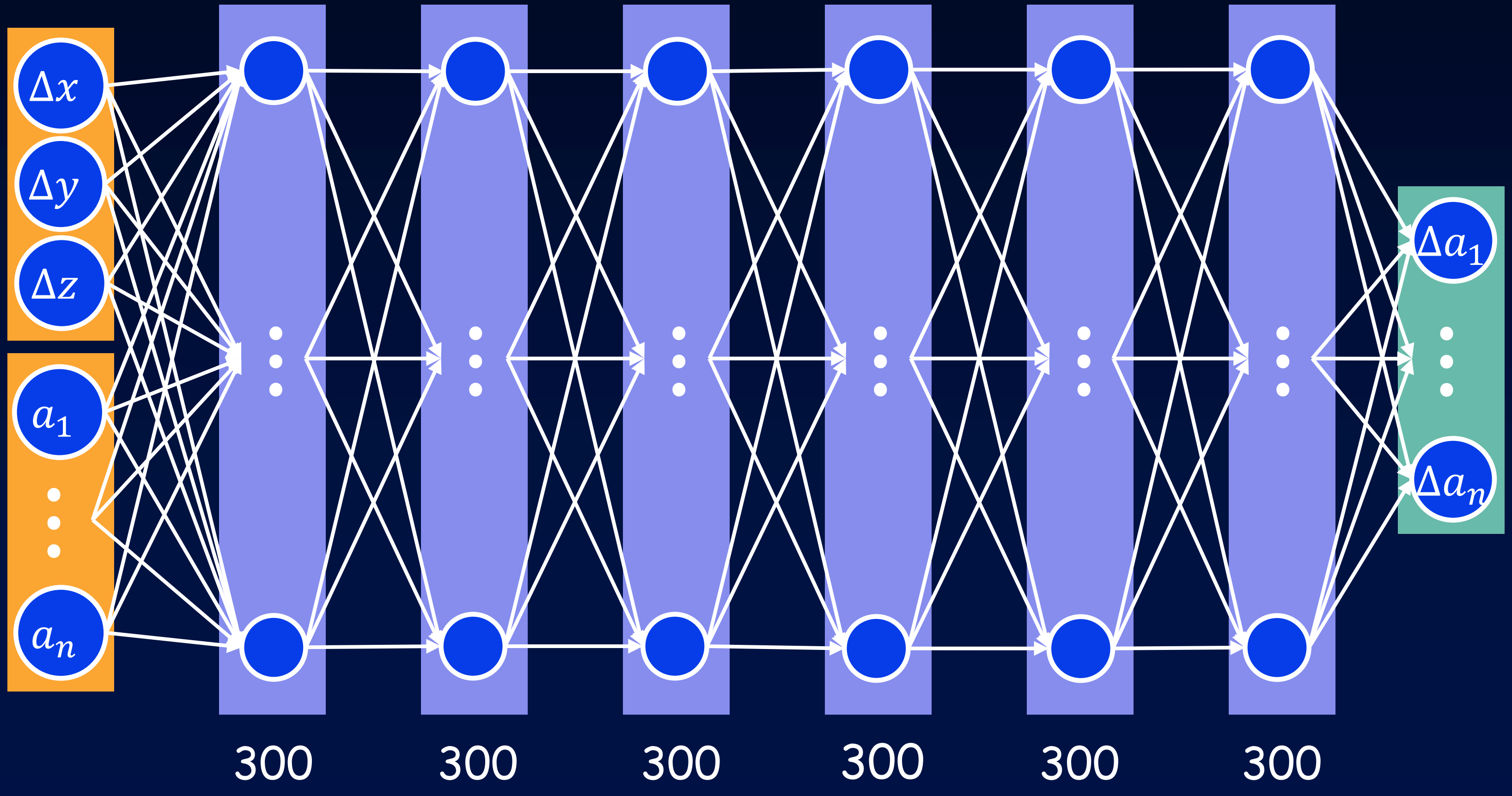
# Cervicocephalic Voluntary Controller DNN

## *Fully-connected DNN architecture*

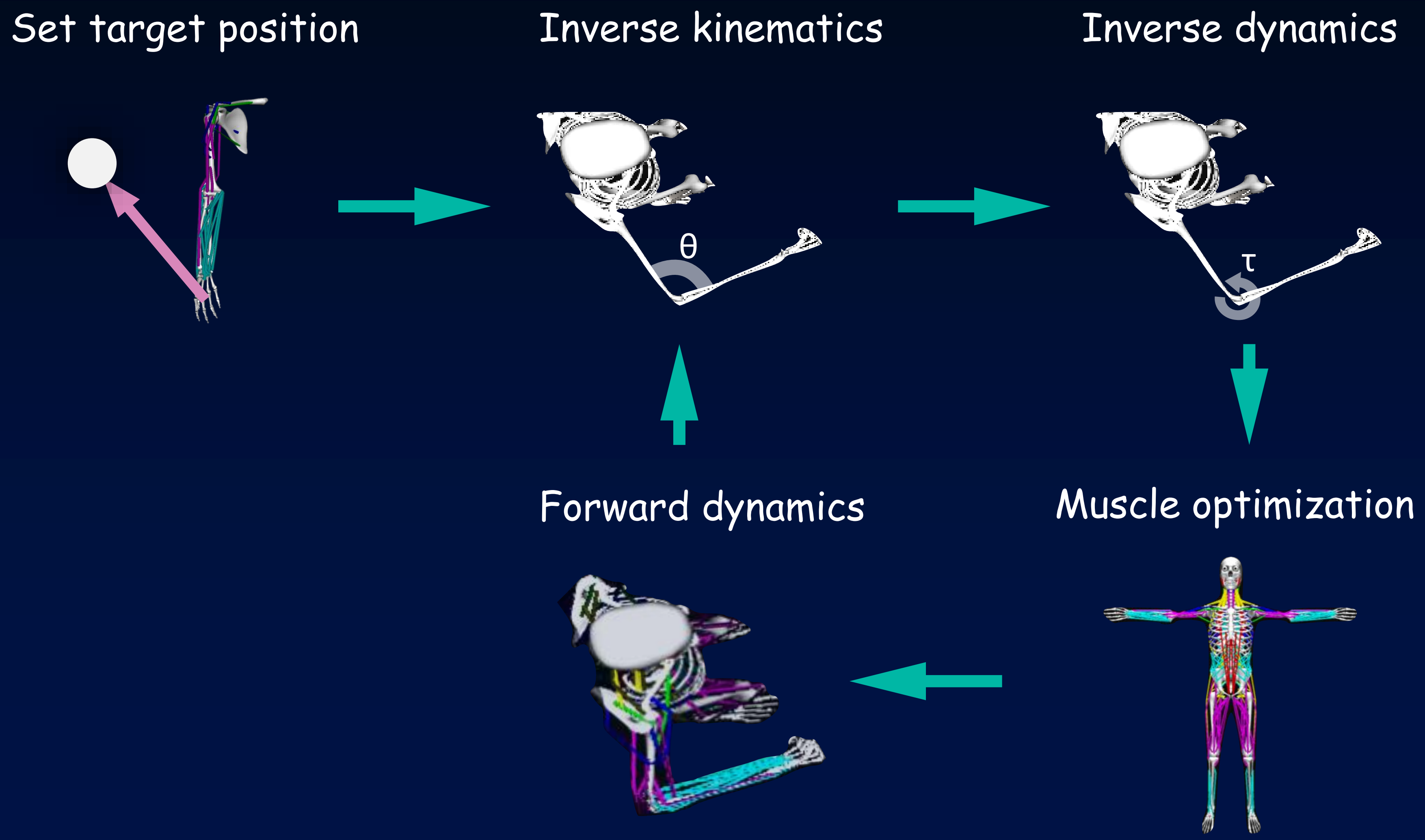


# Limb Voluntary Controller DNN

## Fully-connected DNN architecture

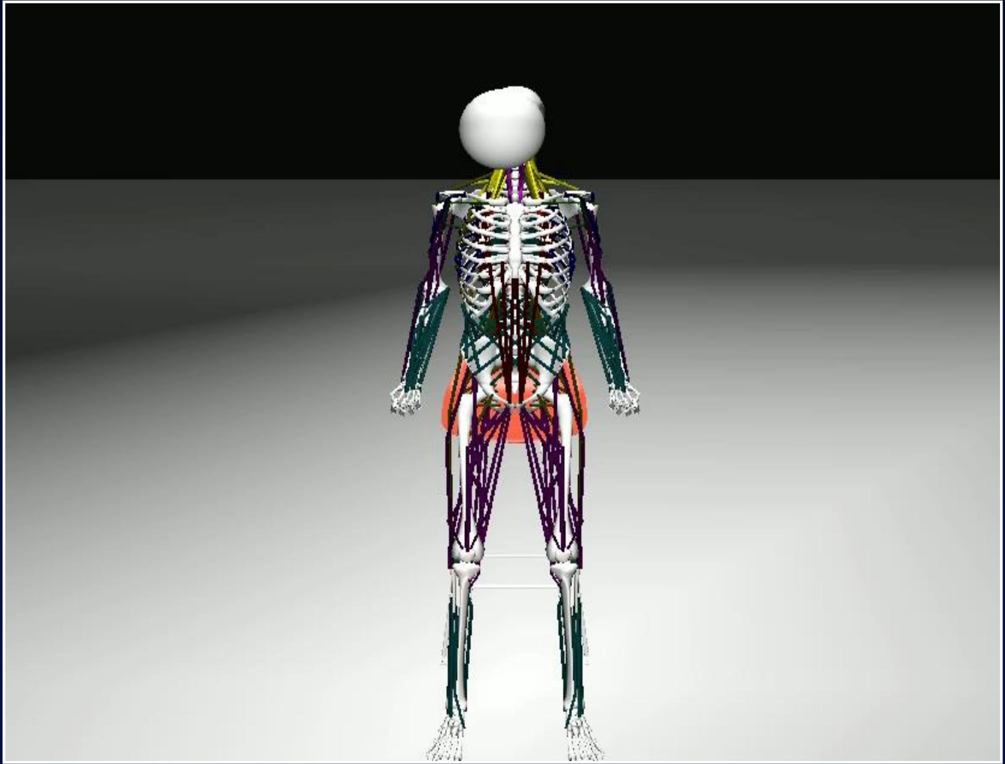


# Offline Training Data Synthesis

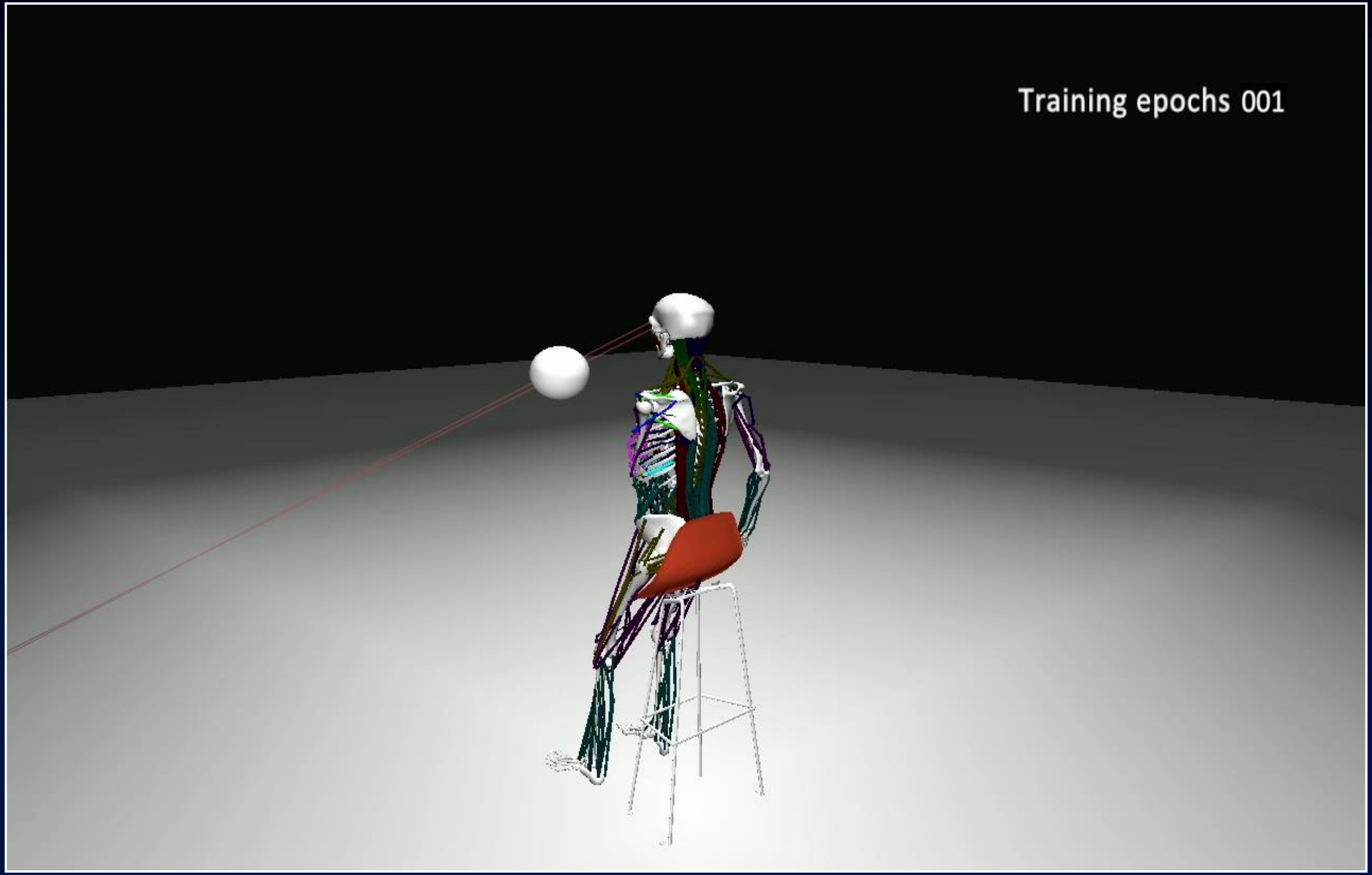


# Untrained Neuromuscular Controllers

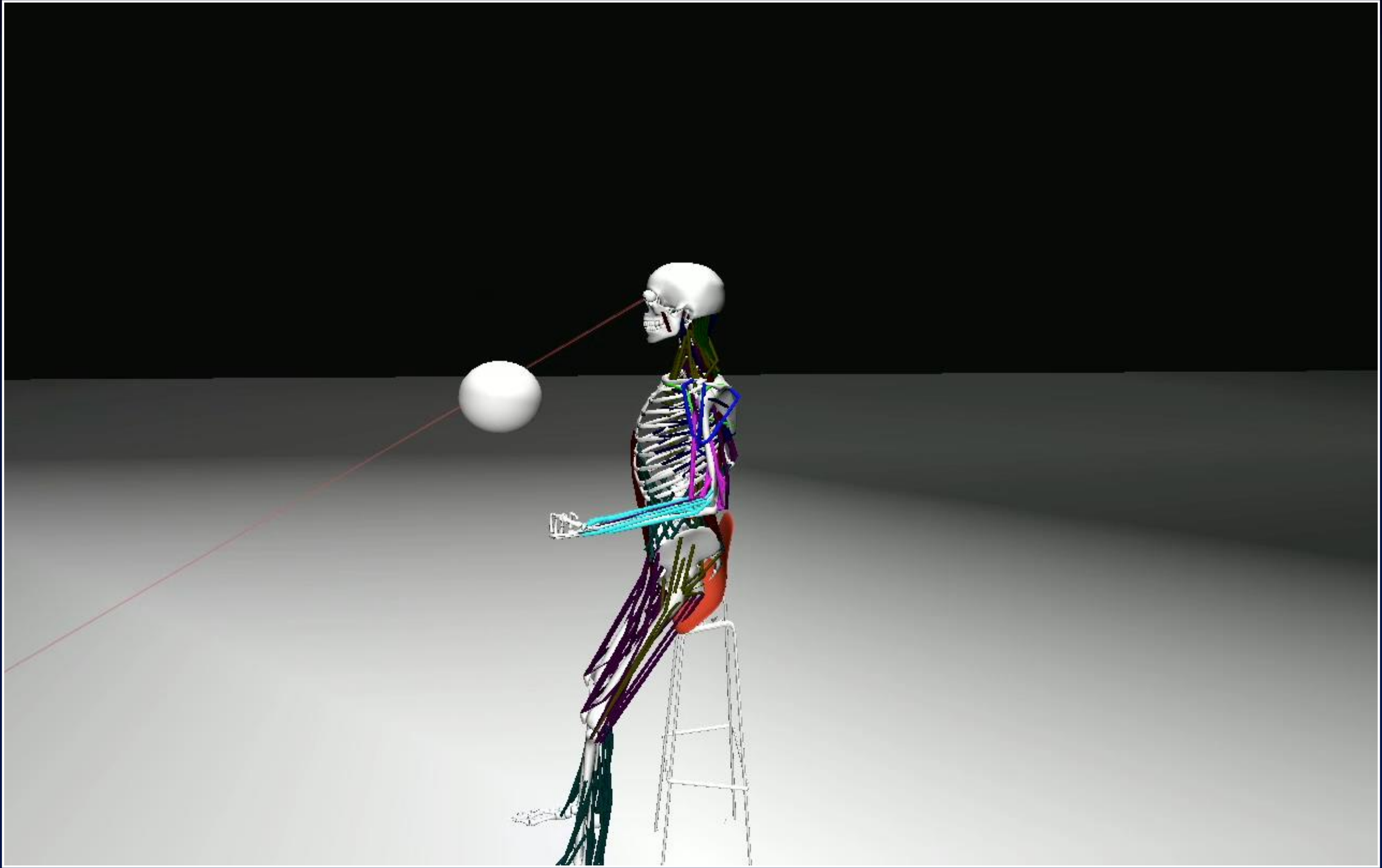
*Musculoskeletal model with immobilized pelvis and thoracic+lumbar spine*



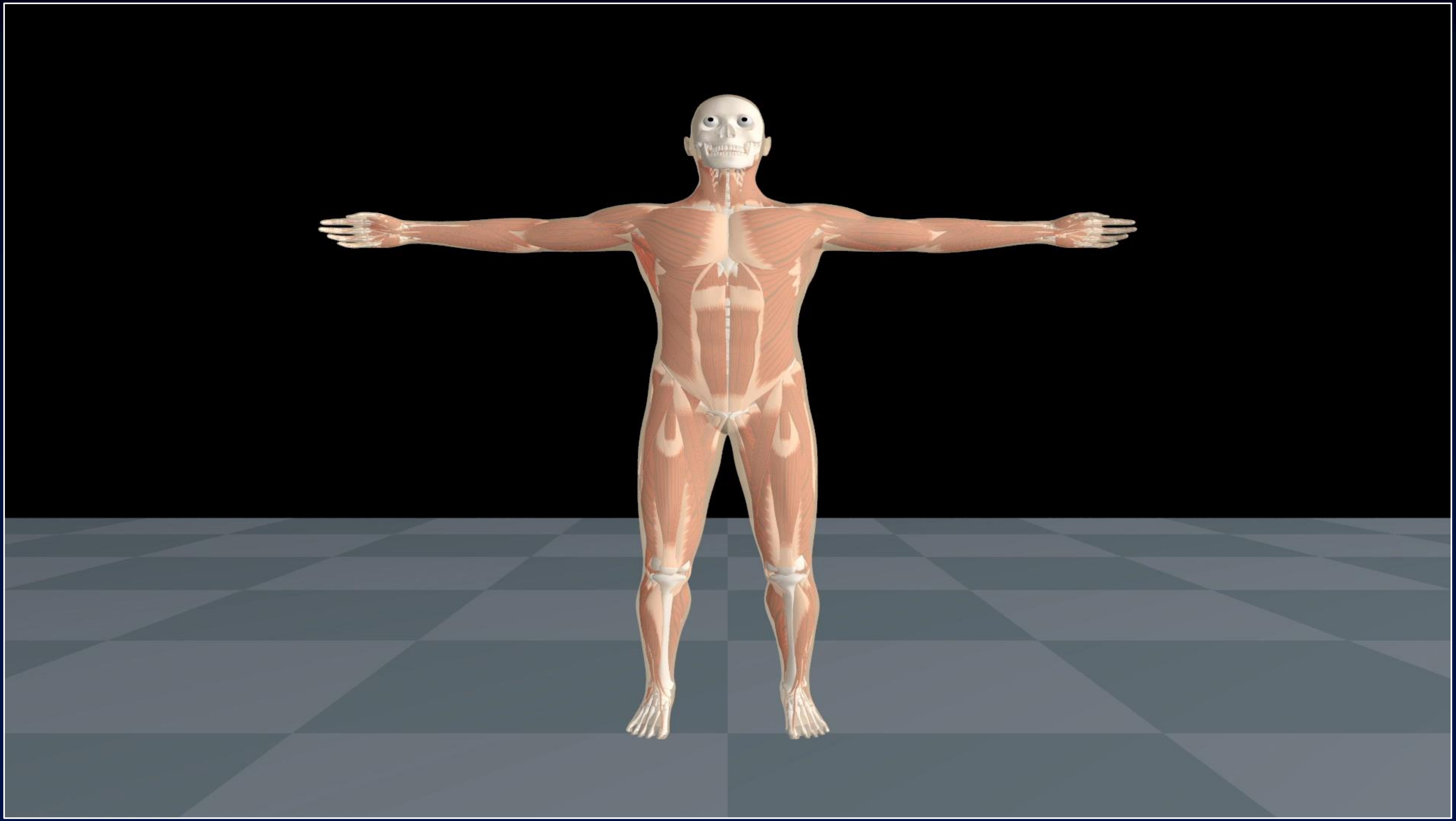
# Progress of the Offline Training Process (for the Left Arm)



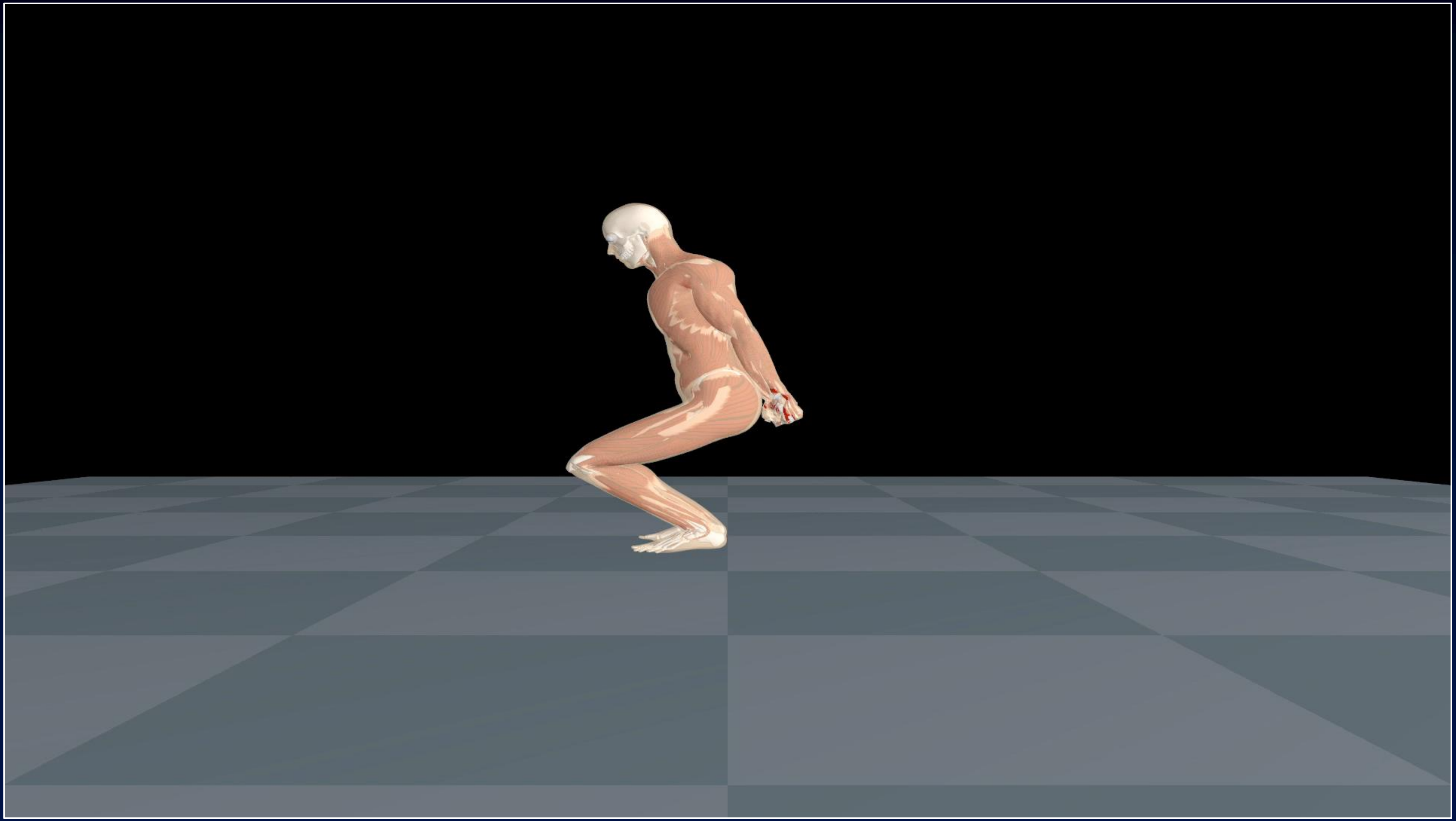
# After 900 Training Epochs



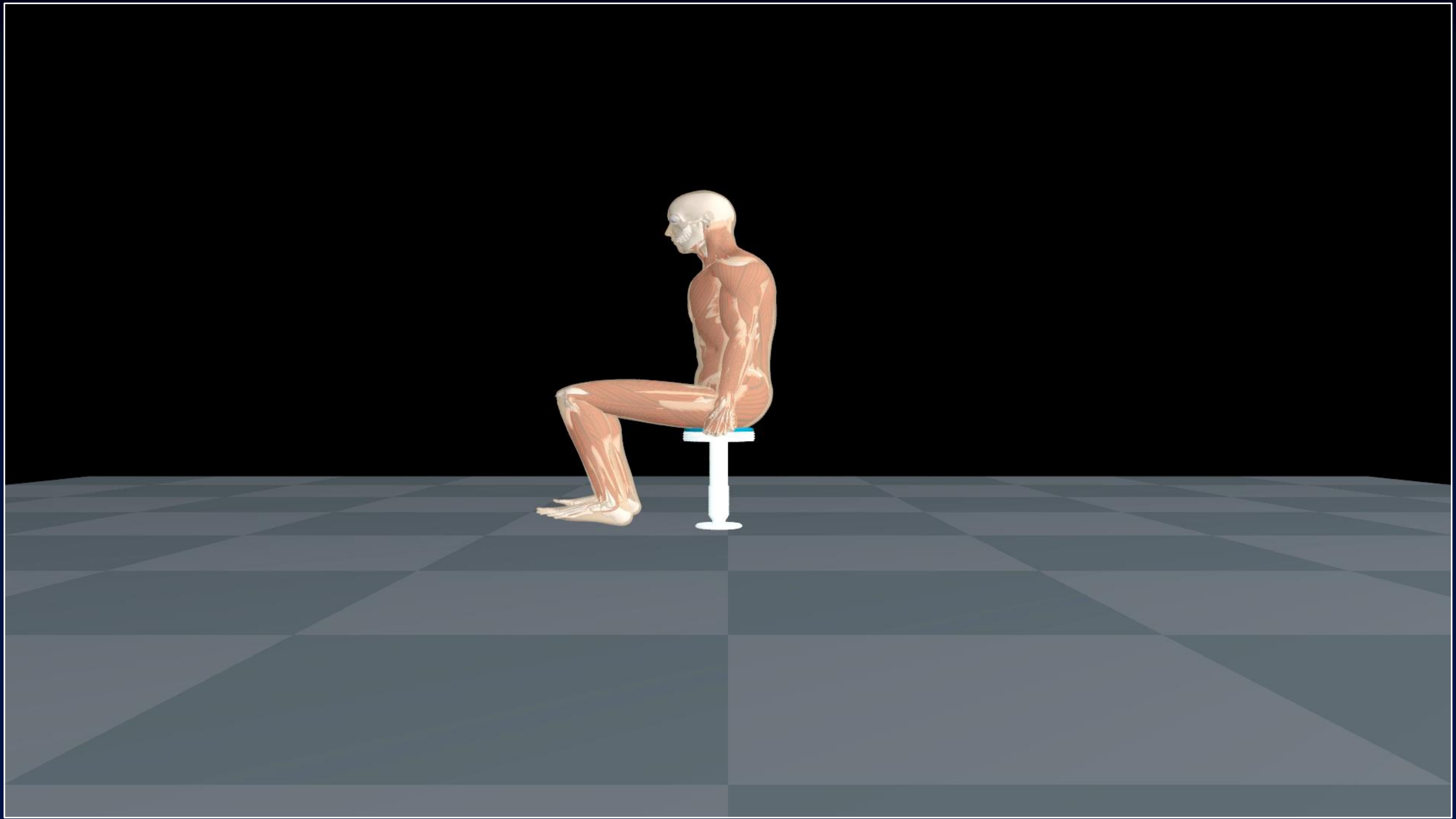
# Torso Calisthenics



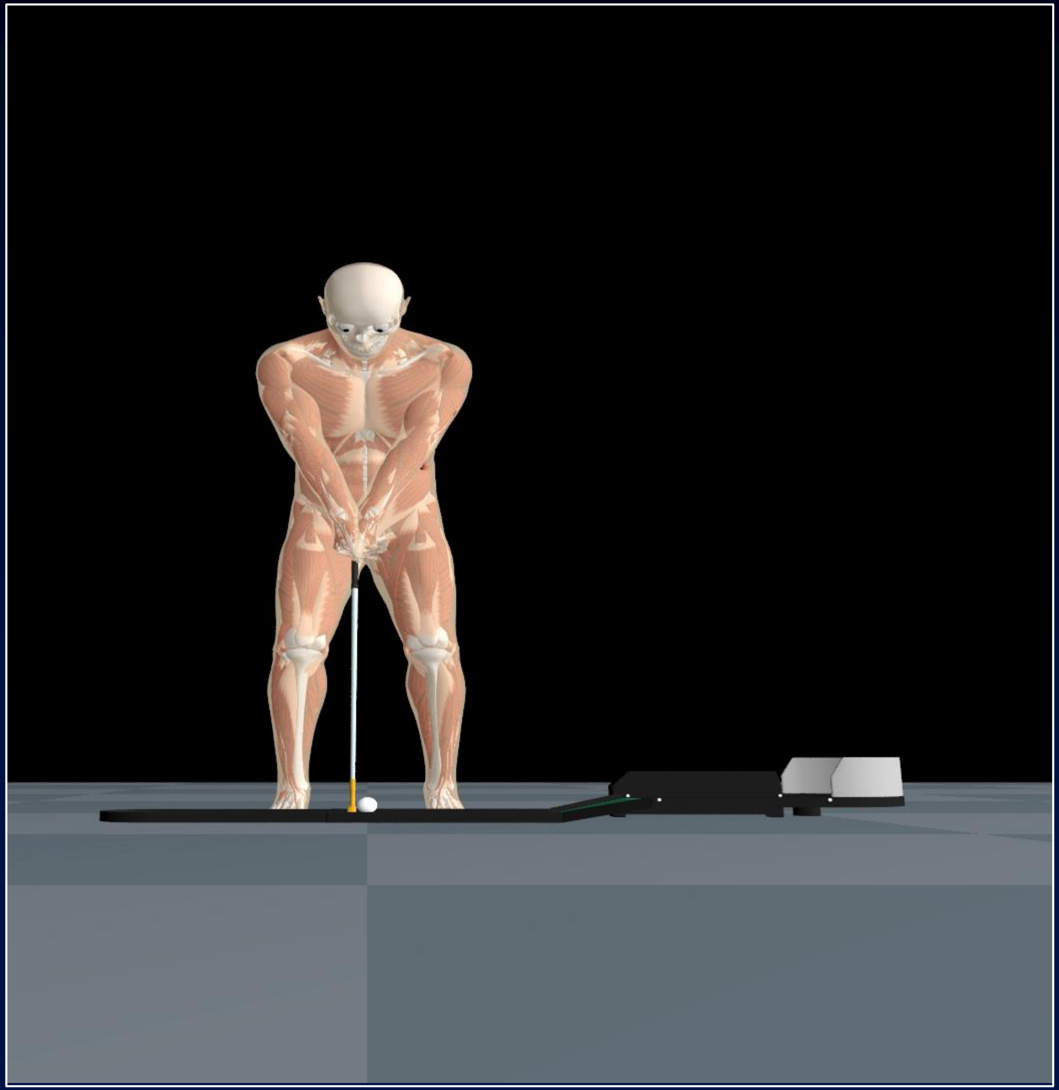
# Sit-to-Stand Motor Controller Training Process

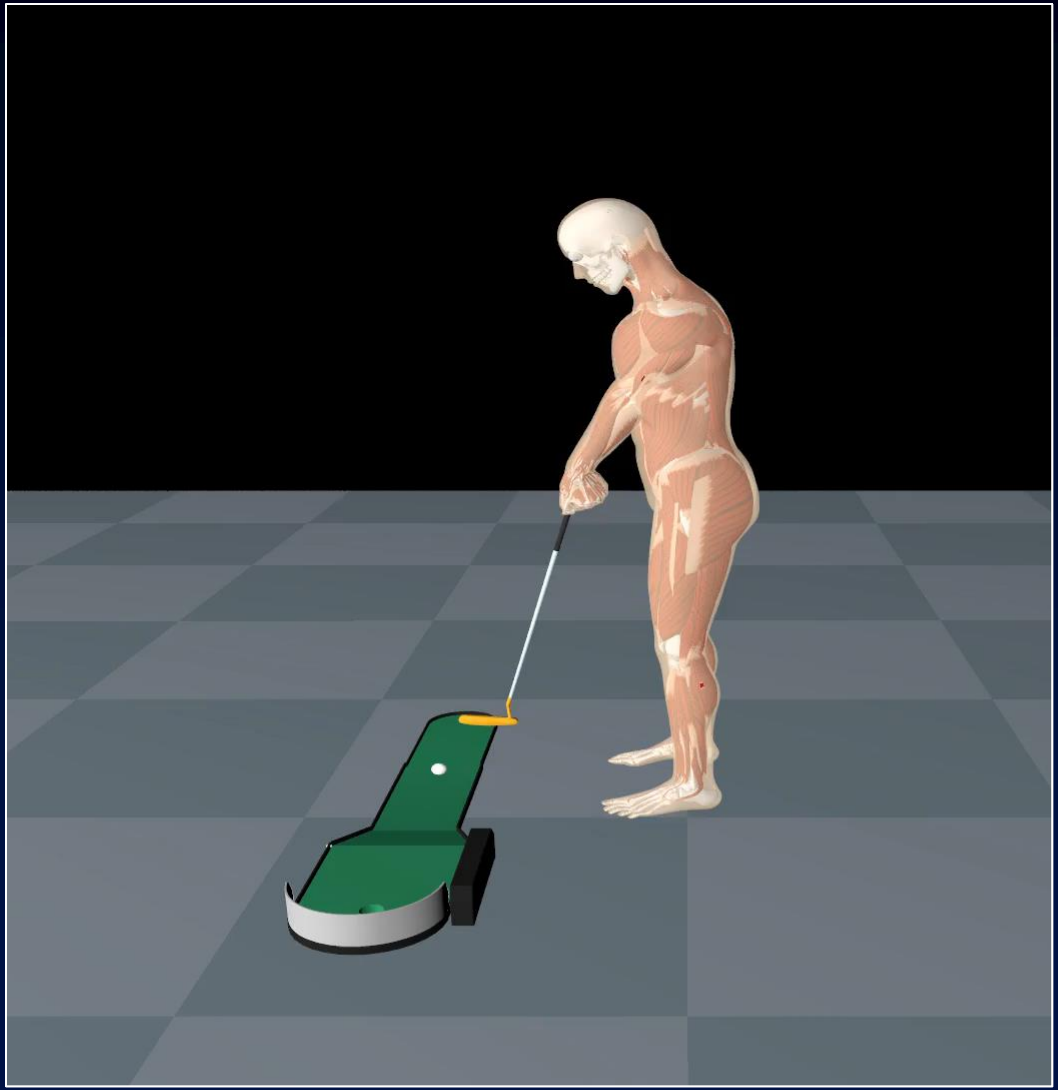


# Trained Sit-to-Stand Motor Controller

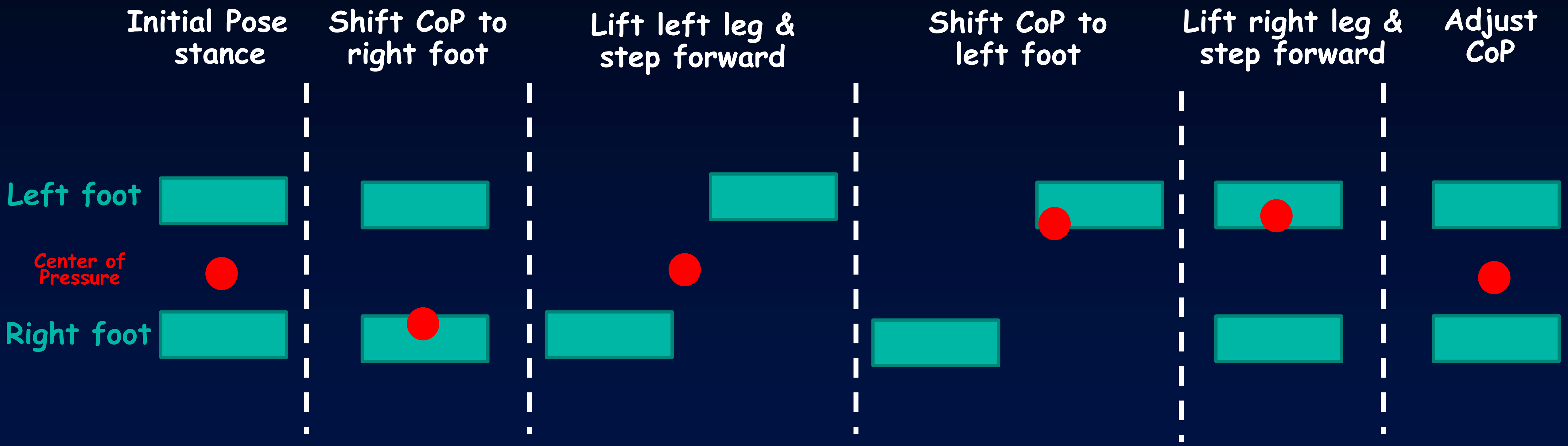


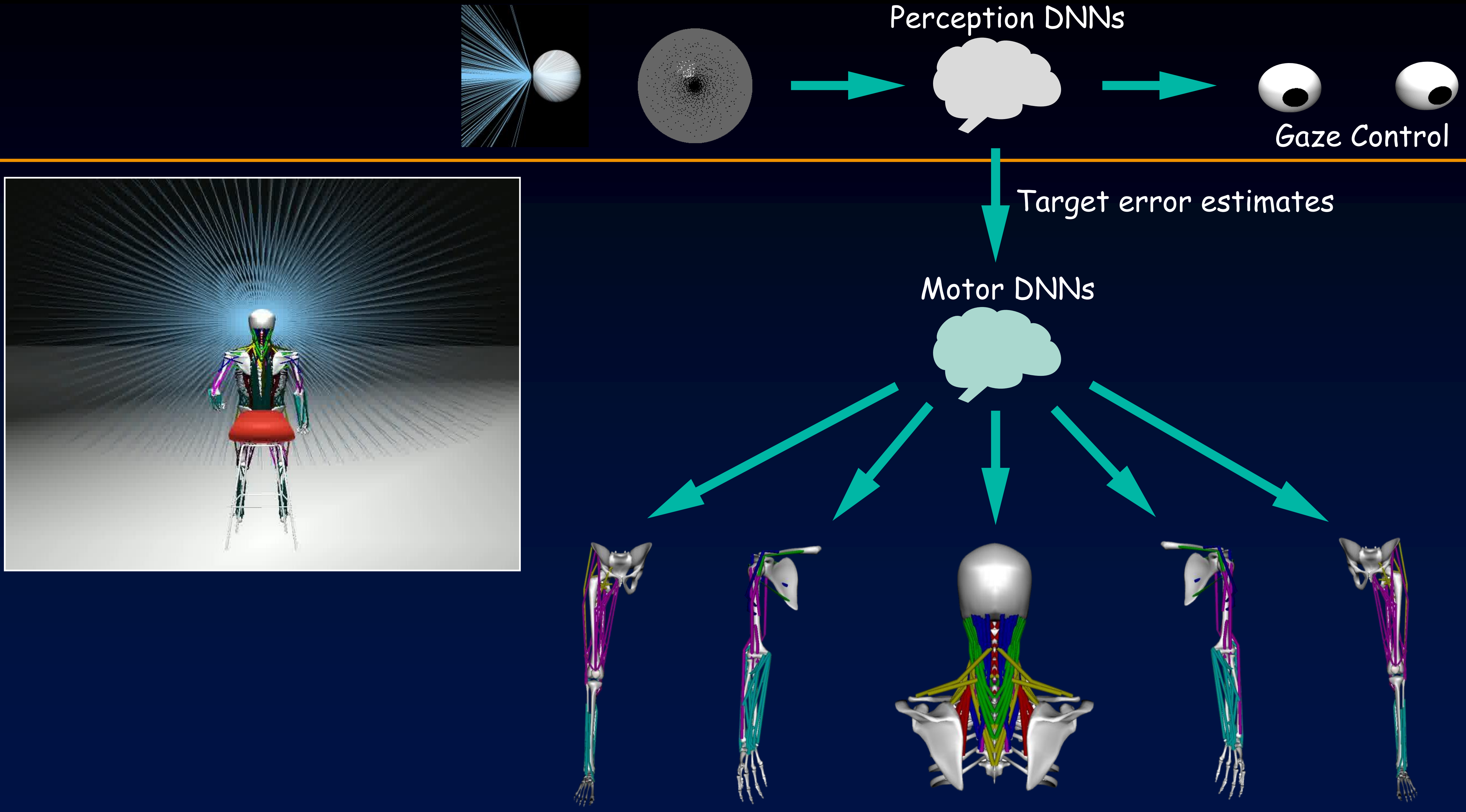
# Golf Putting





# Stepping Voluntary Controller




Perception DNNs
Gaze Control
Target error estimates
Motor DNNs

# Biomimetic Vision

## *The Eye and its Retina*

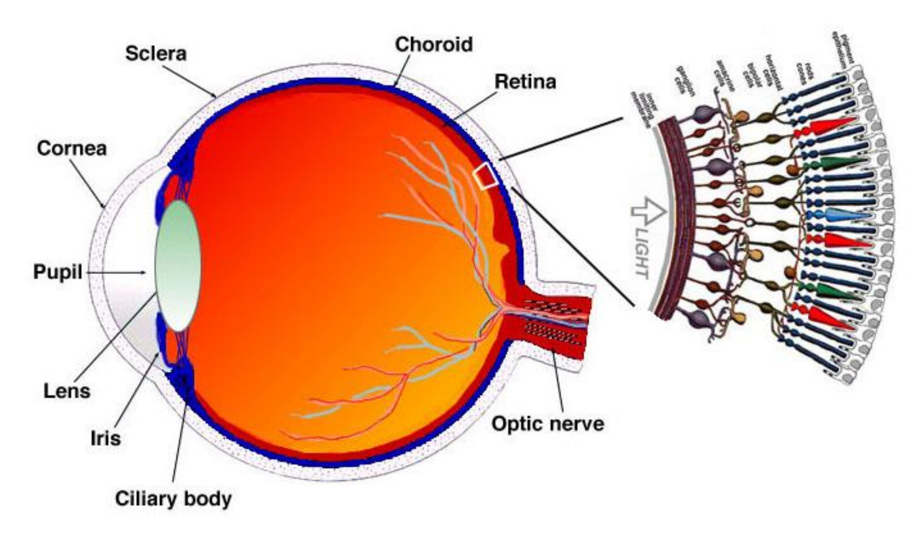



*Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.*

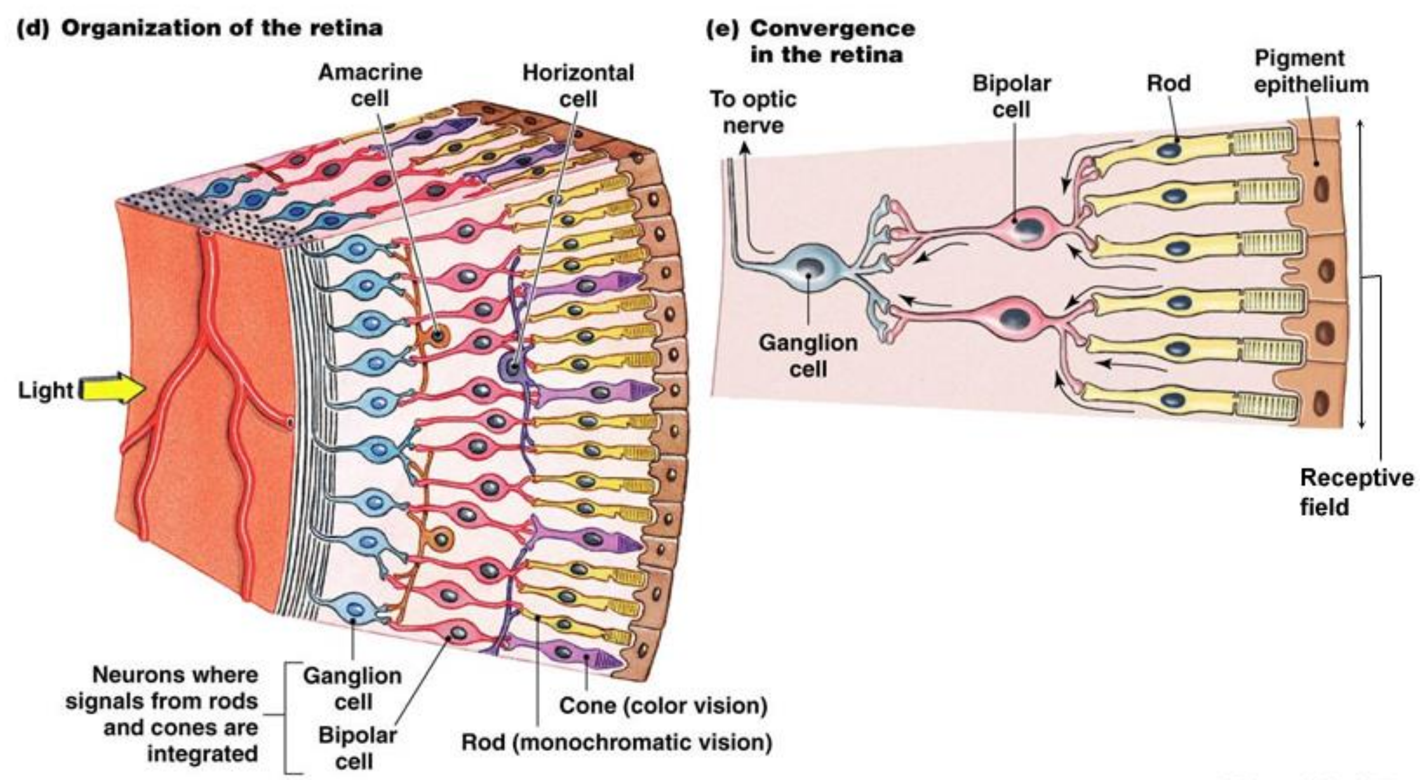
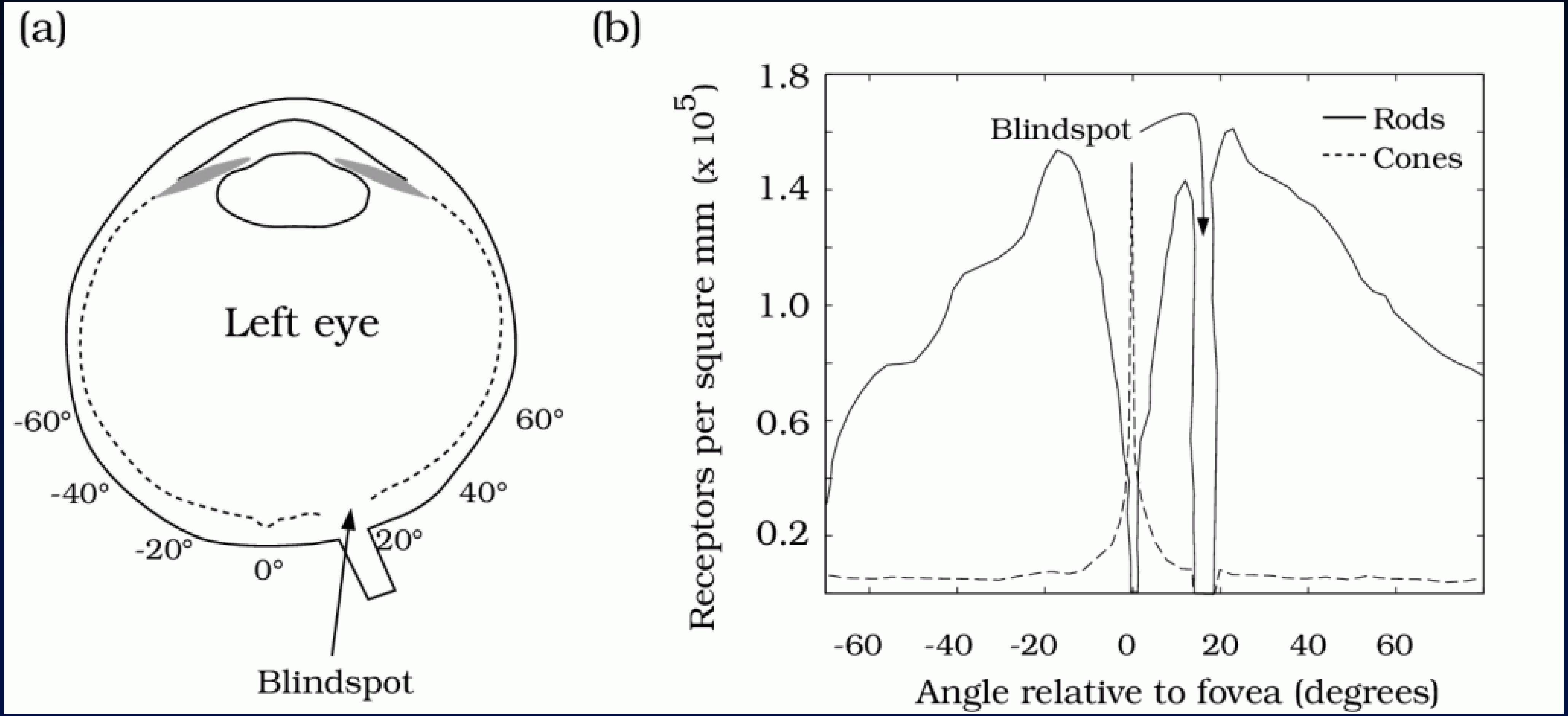




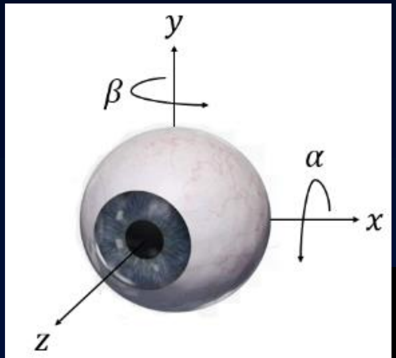

Fig. 10-35

# Retinal Photoreceptor Distribution

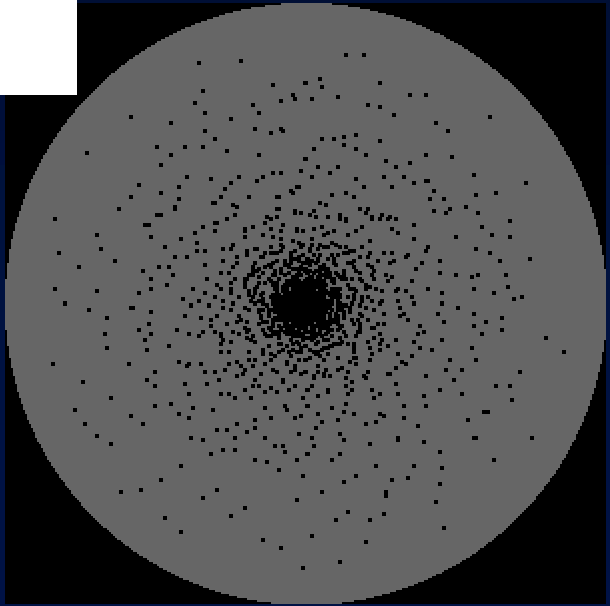


# Photoreceptor Distribution Model

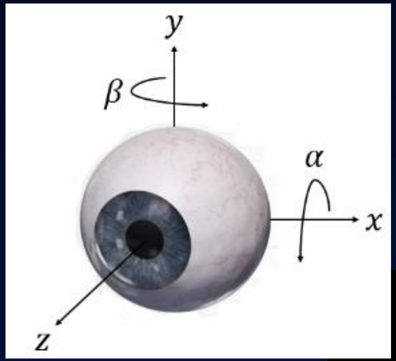
## *Noisy log-polar (spiral) distribution*



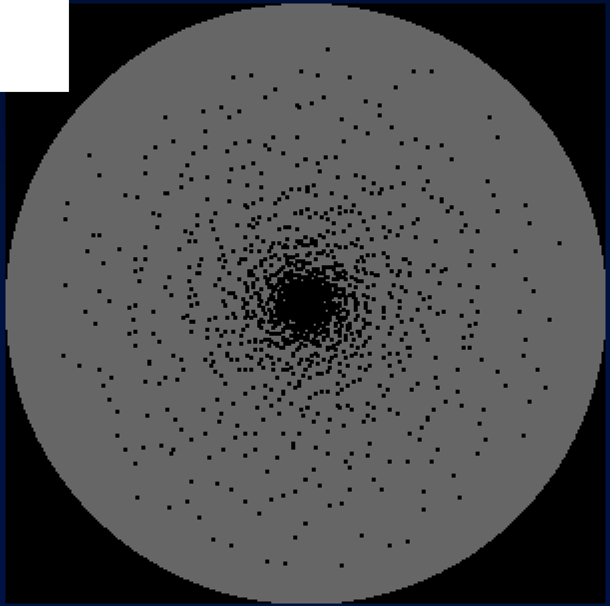

Left Retina



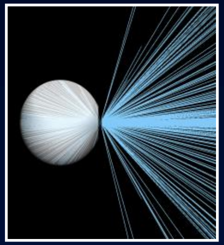
$P$ = 3,600
Photoreceptors

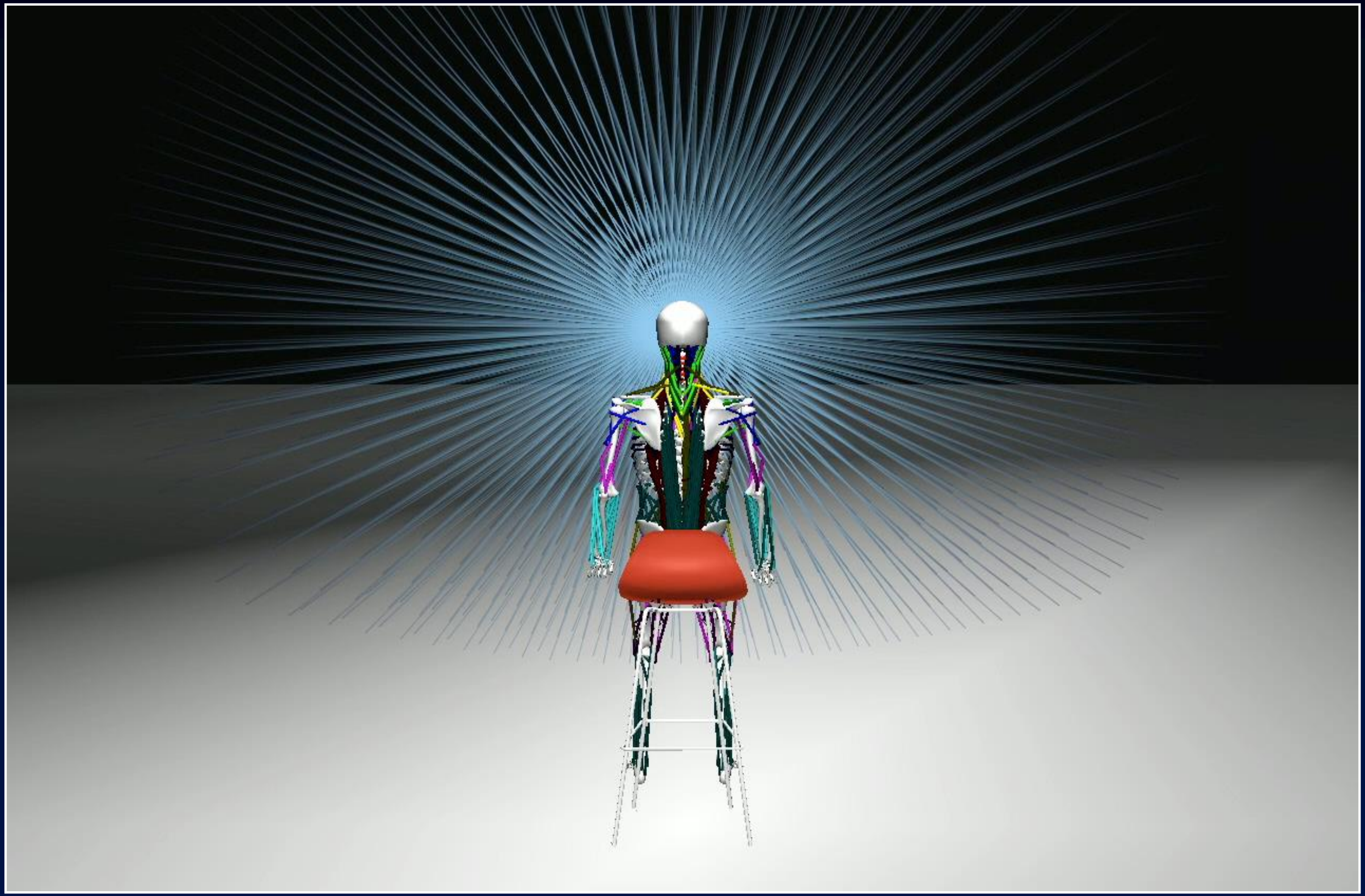



Right Retina



# Raytracing into the 3D Environment to Compute Irradiance at the Photoreceptors

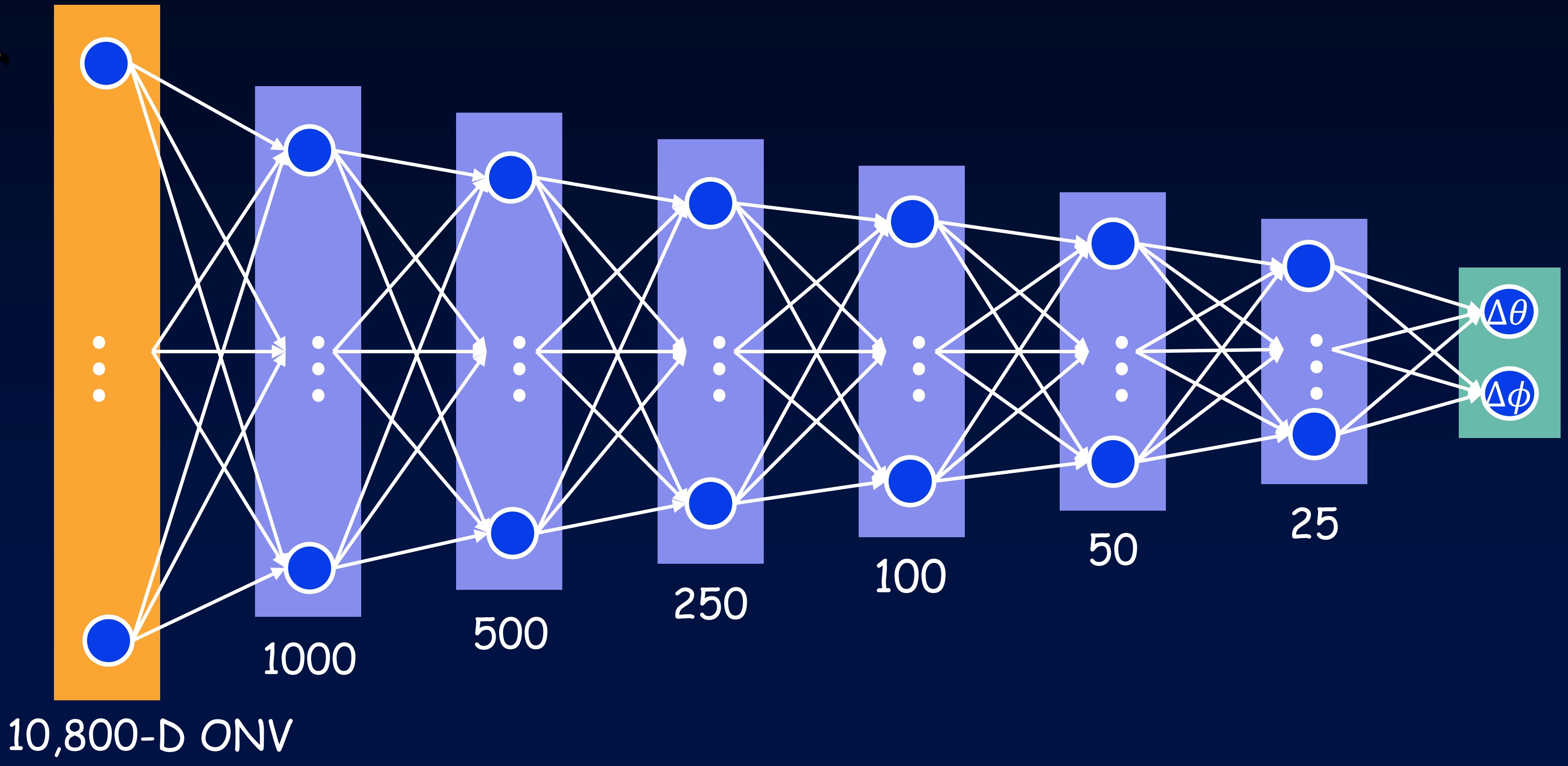




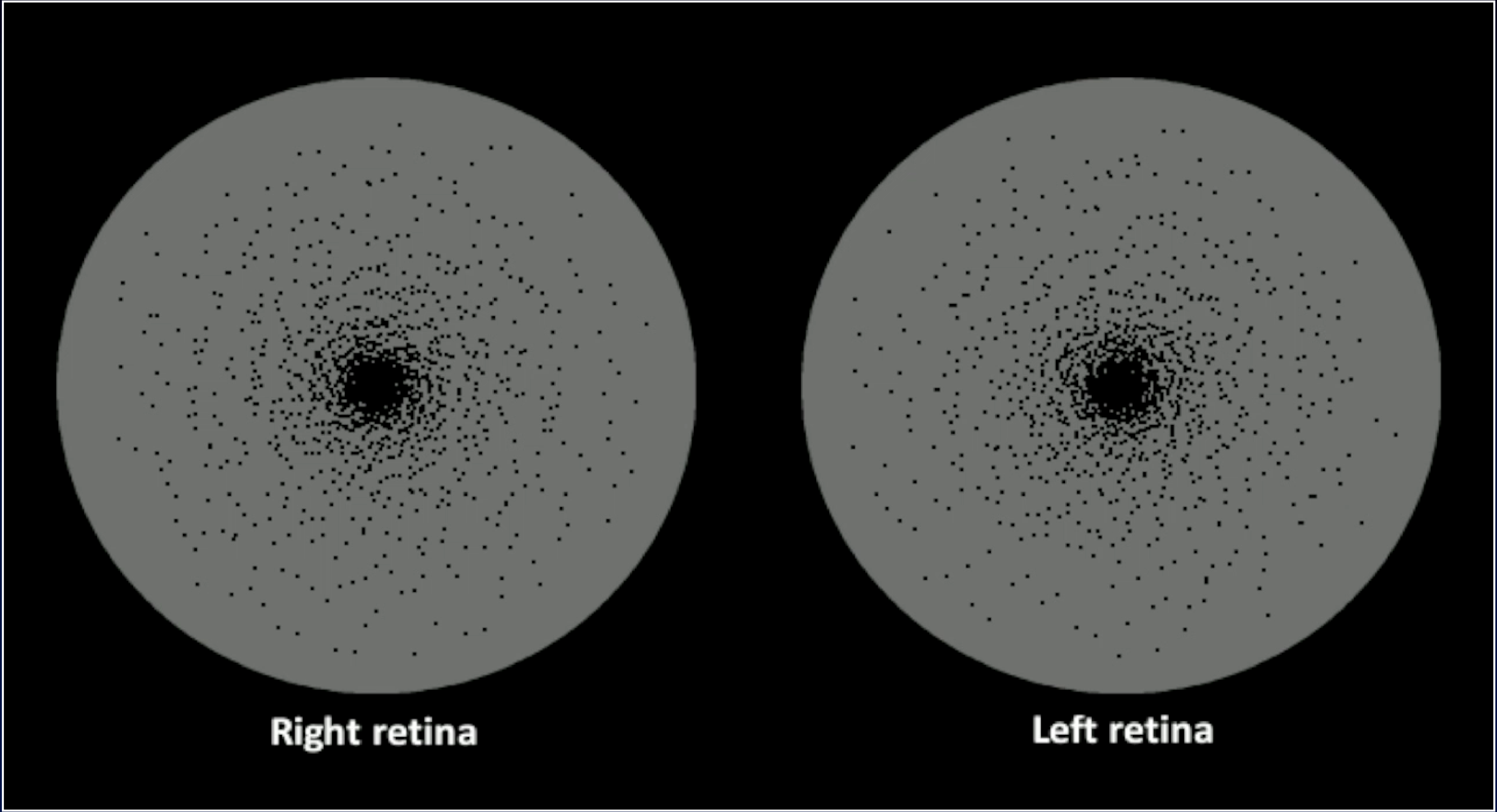
# Perception Controller DNNs

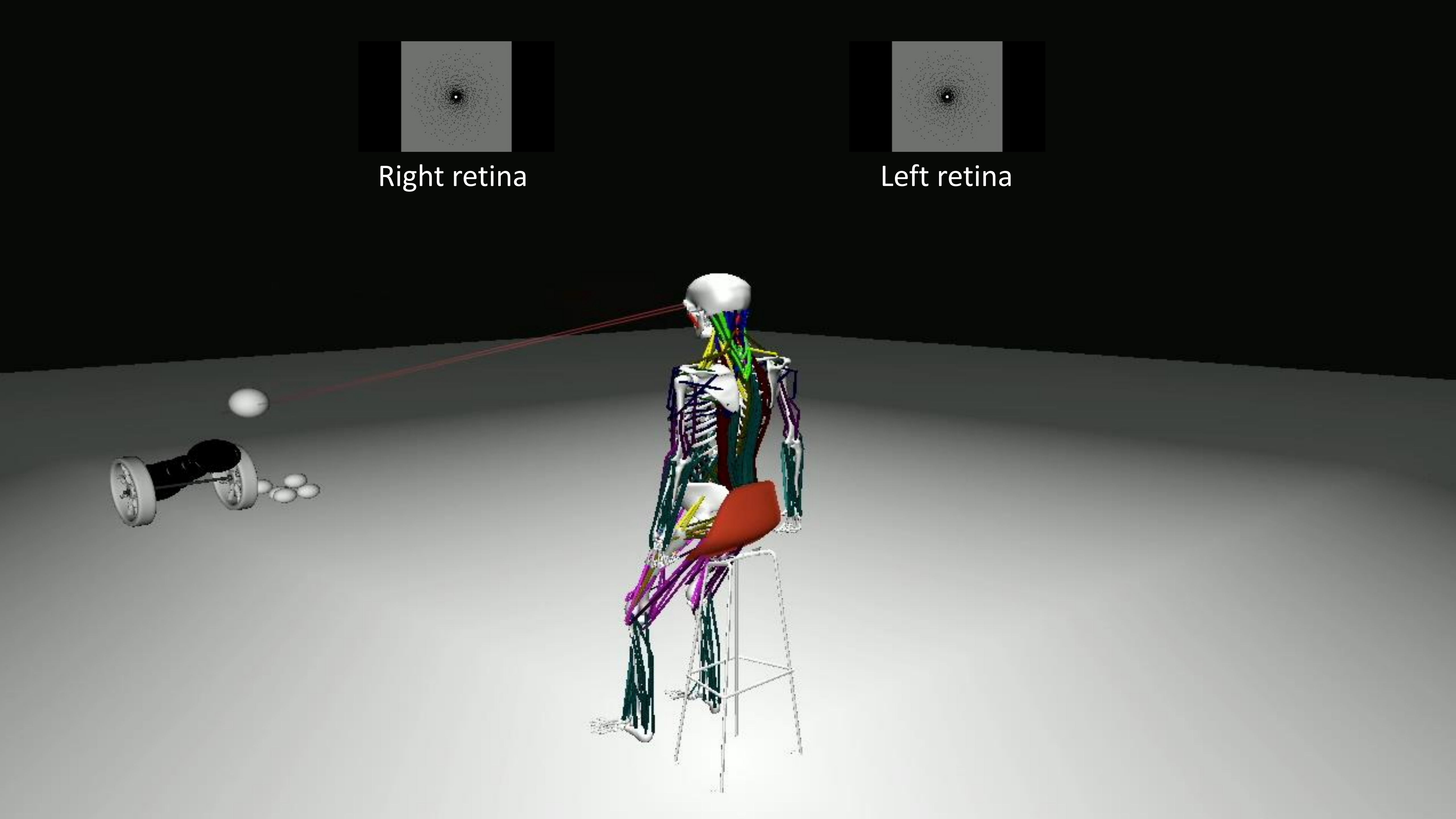
## *Foveation DNN*

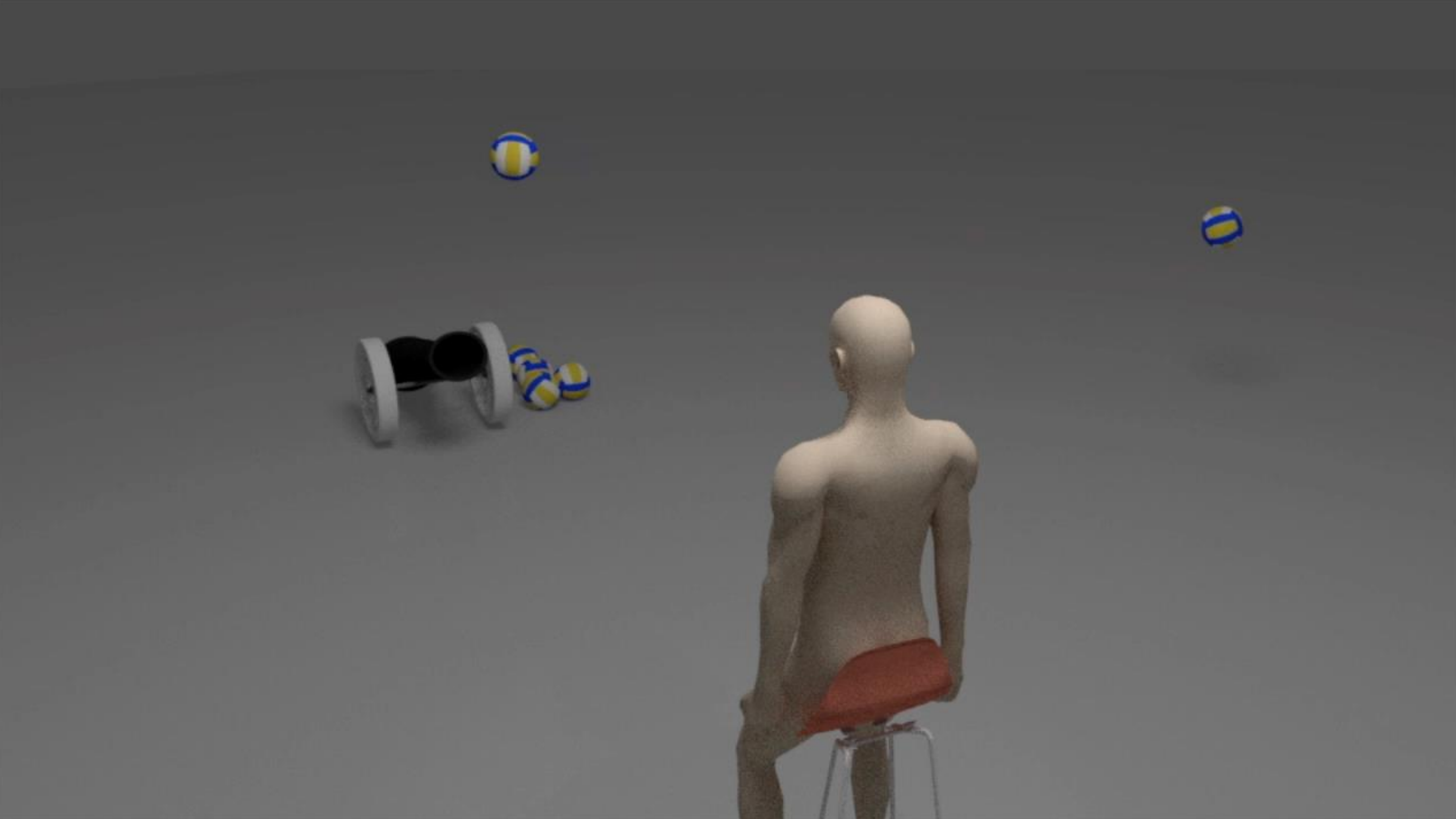
- Optical Nerve Vector (ONV) input
- Eye rotation angles output
- Fully-connected 6-layer DNN

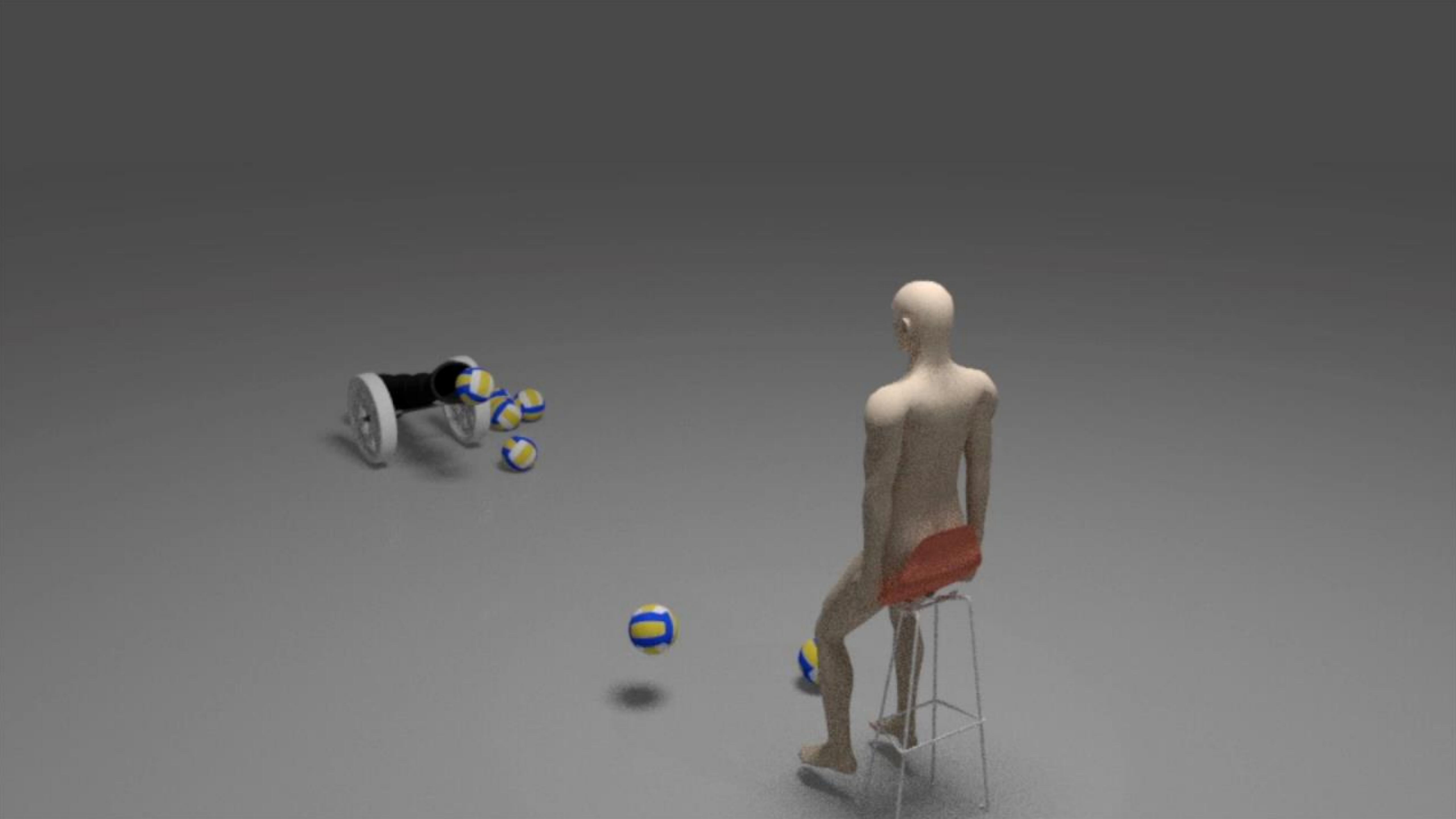


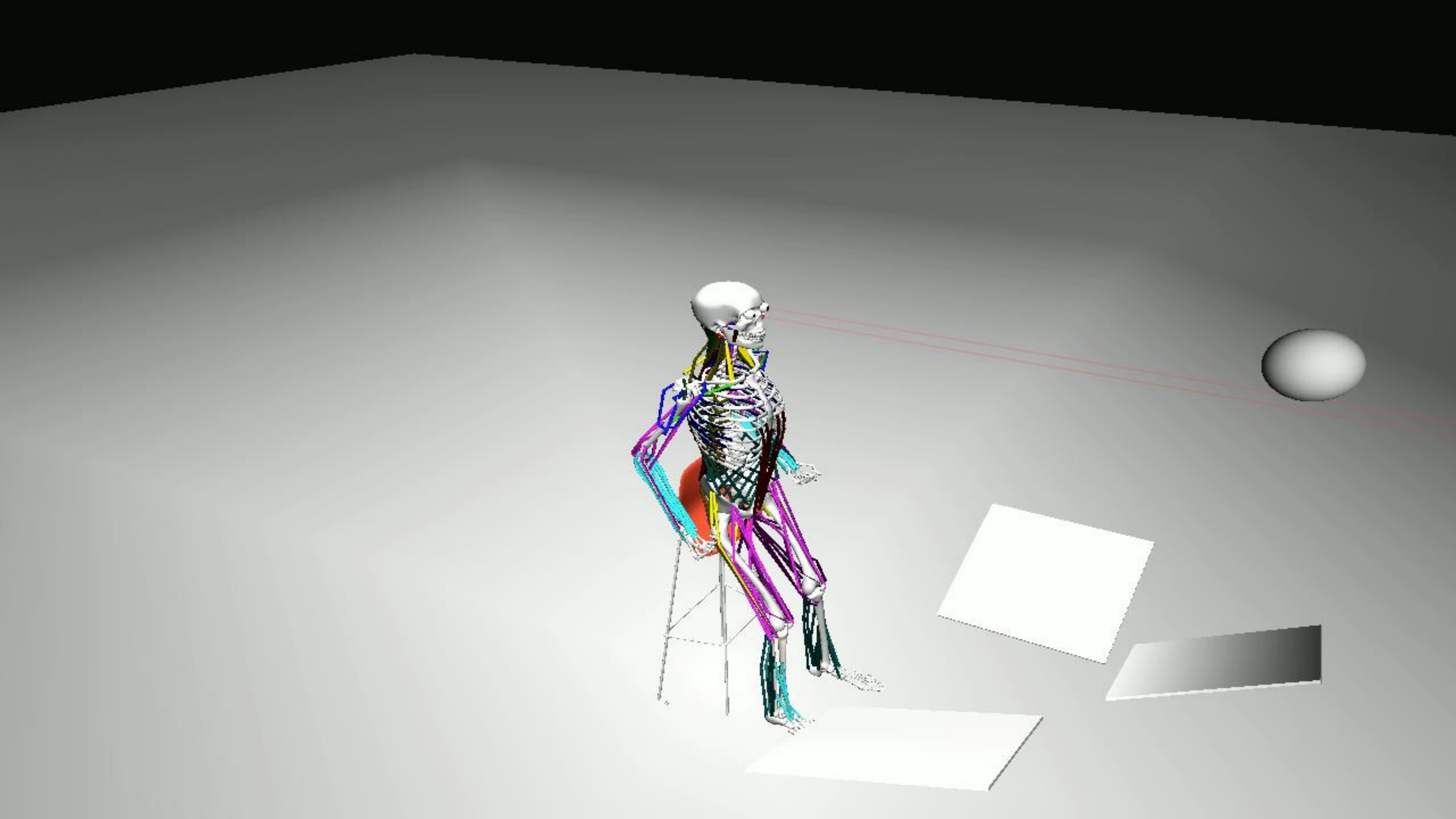
# Learned Foveation Control

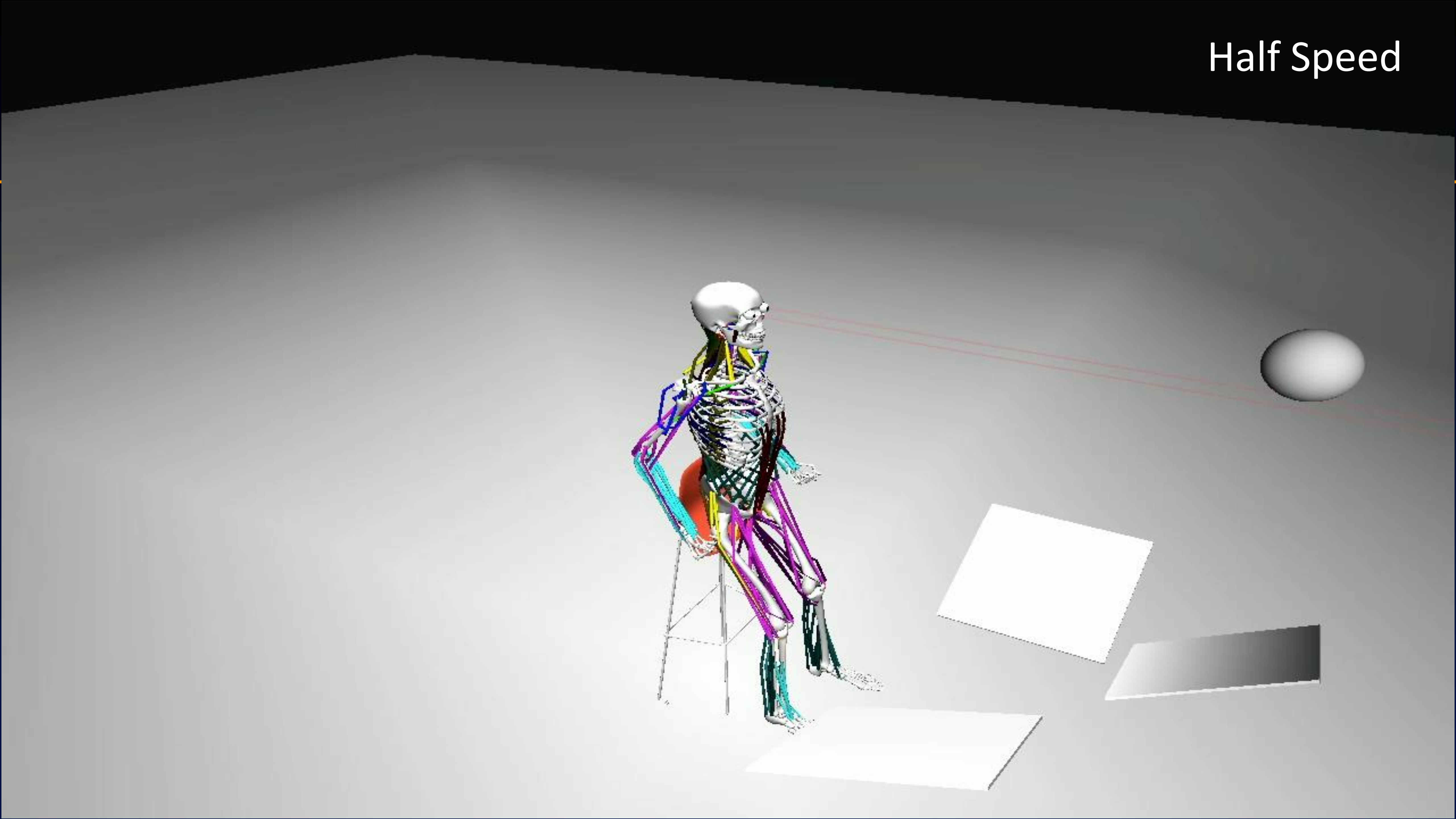


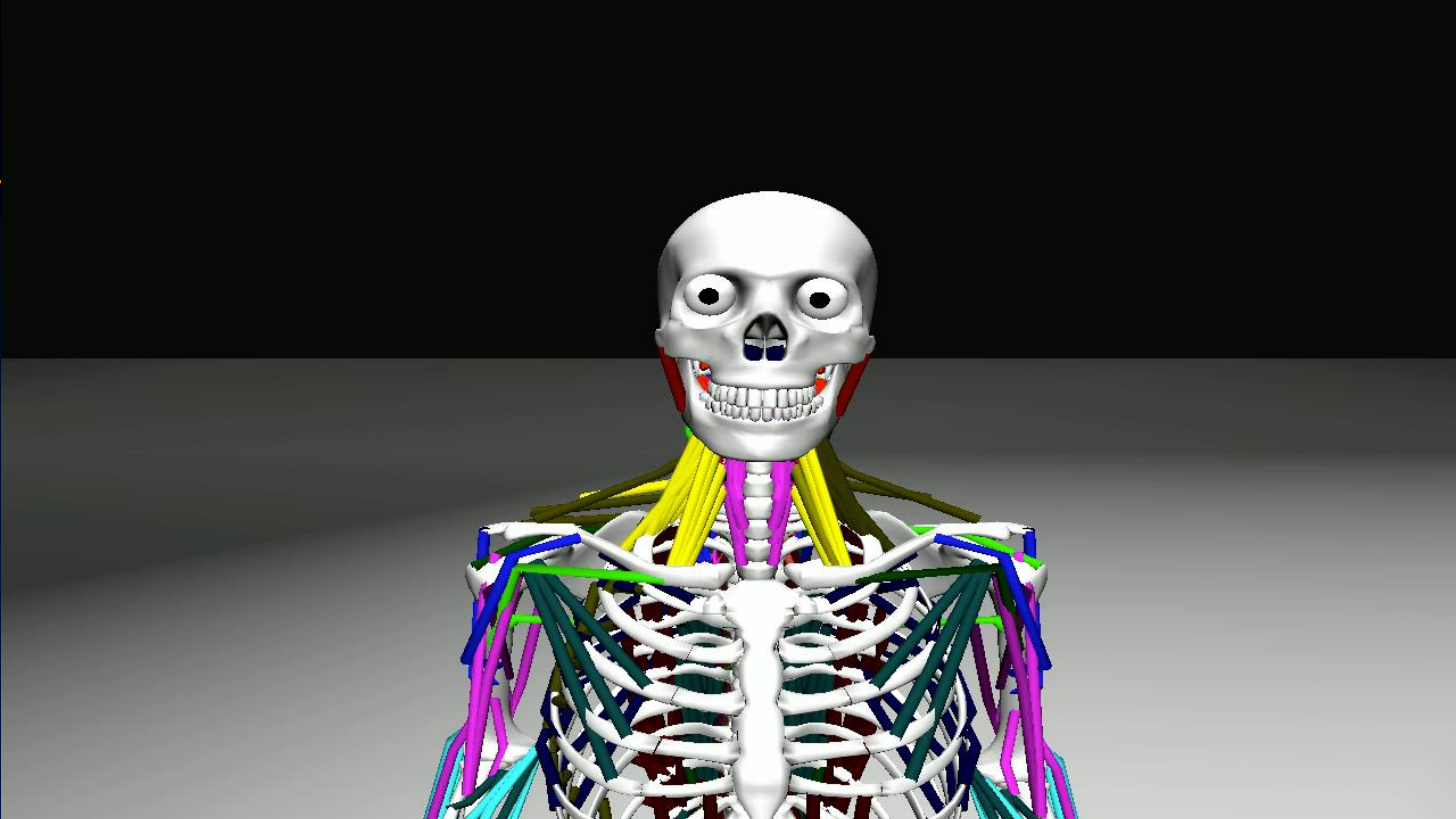

Right retina
Left retina

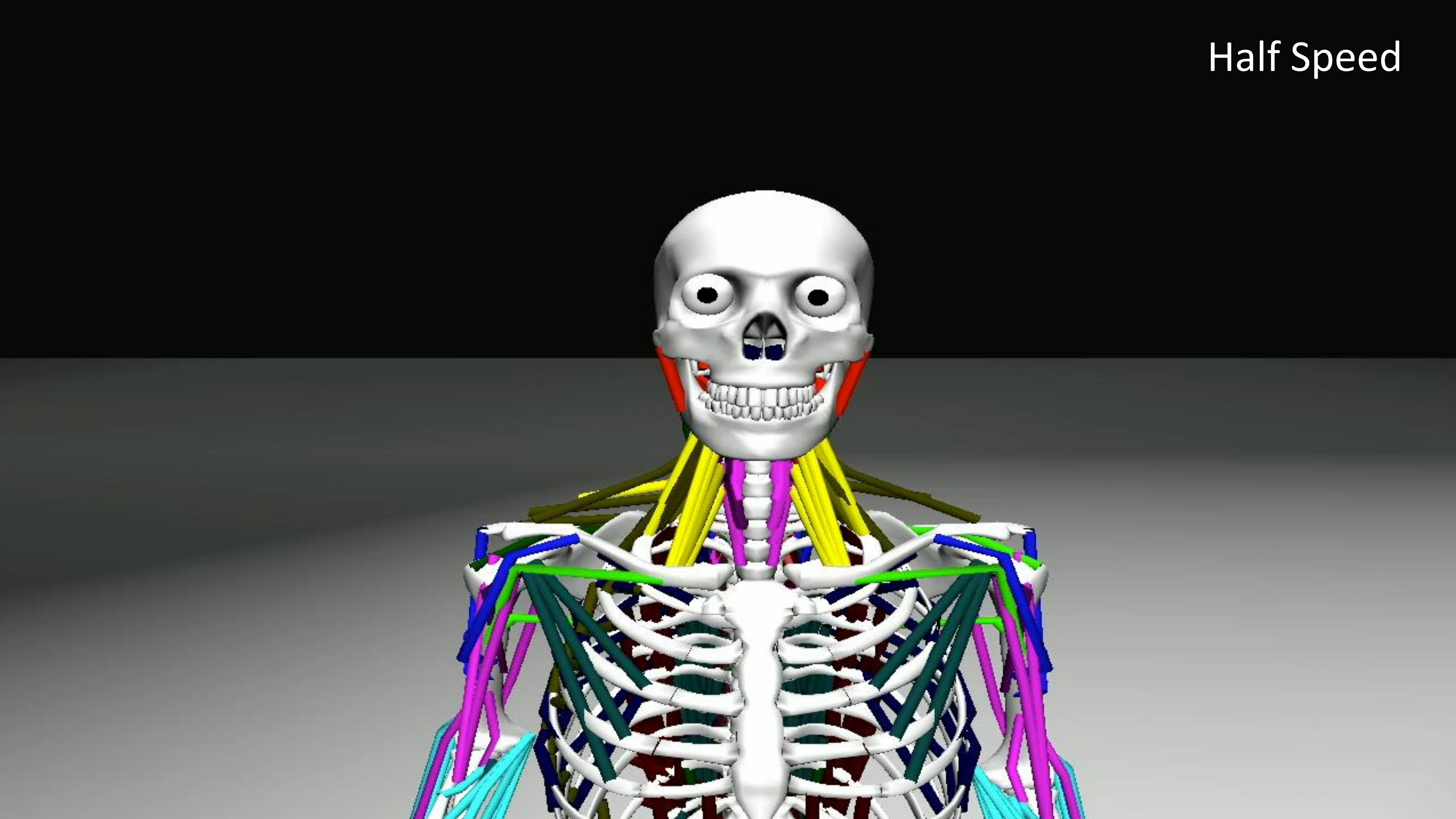


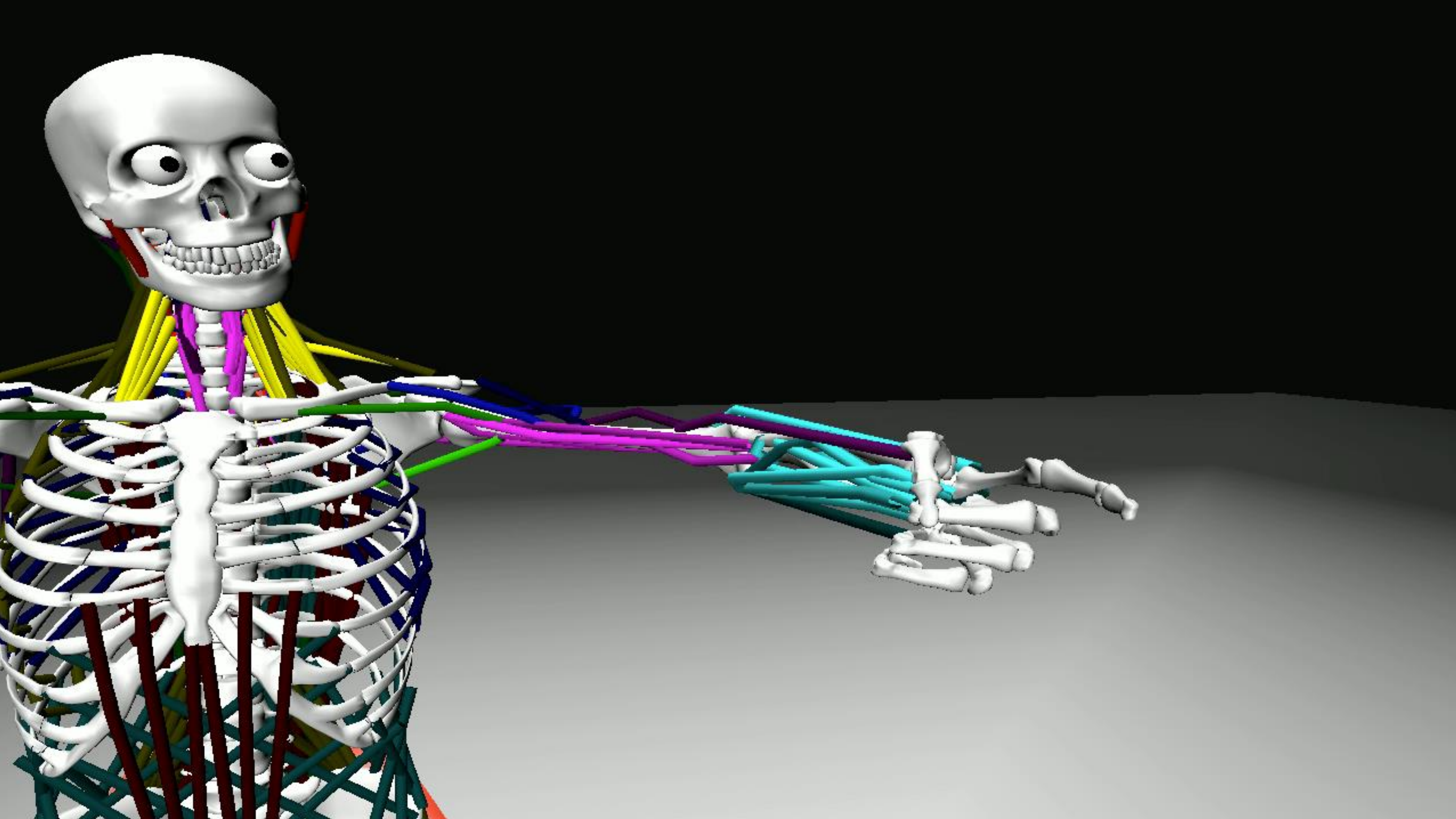


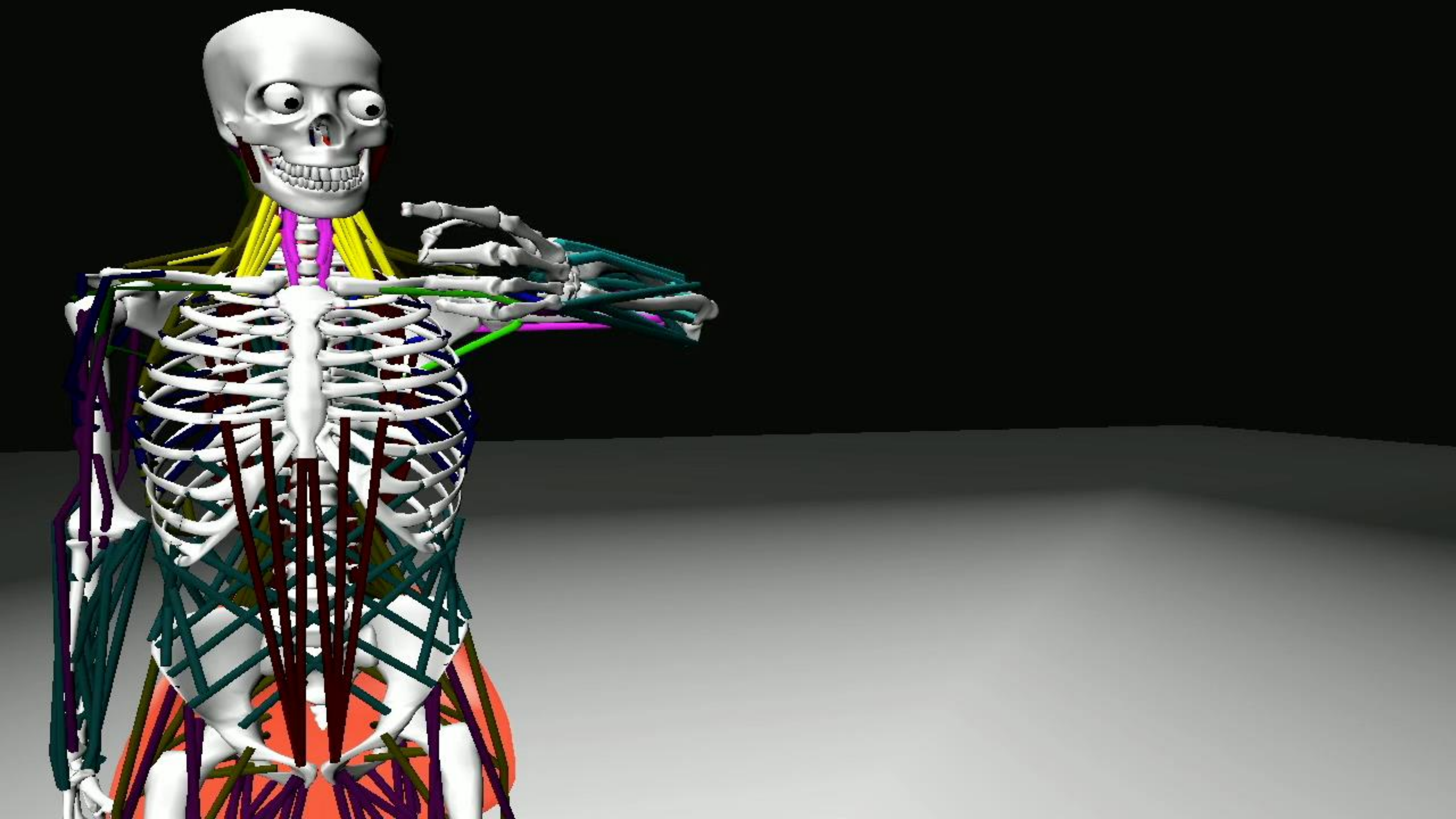



Half Speed

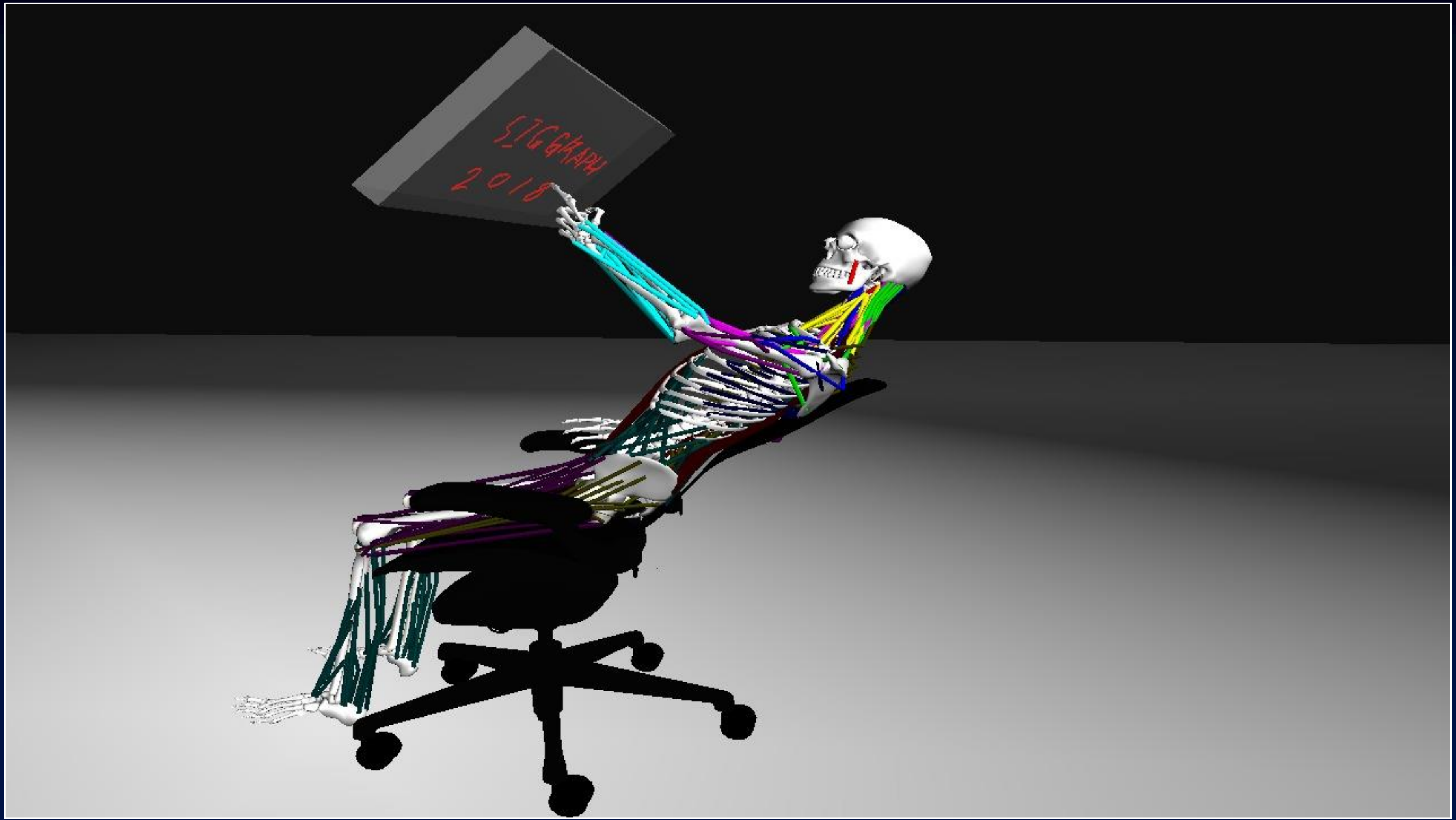



Half Speed



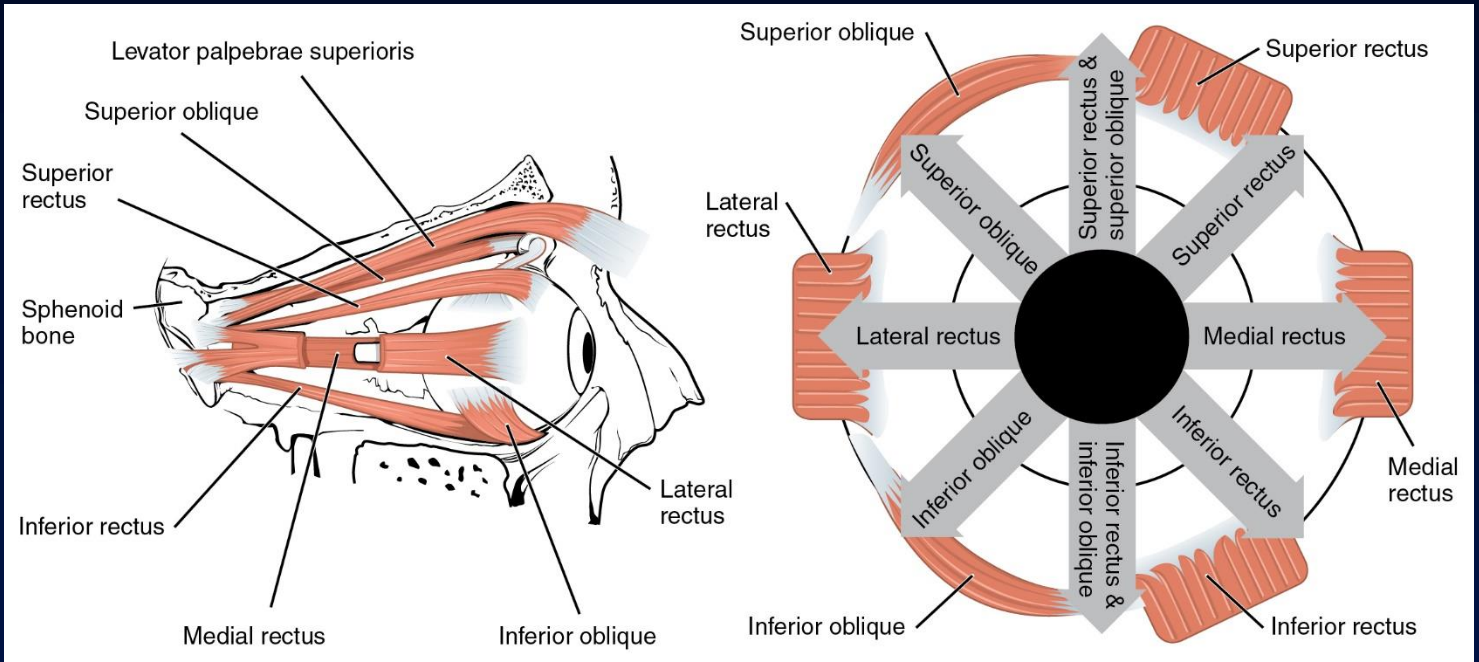


# Robustness of the Trained Controllers



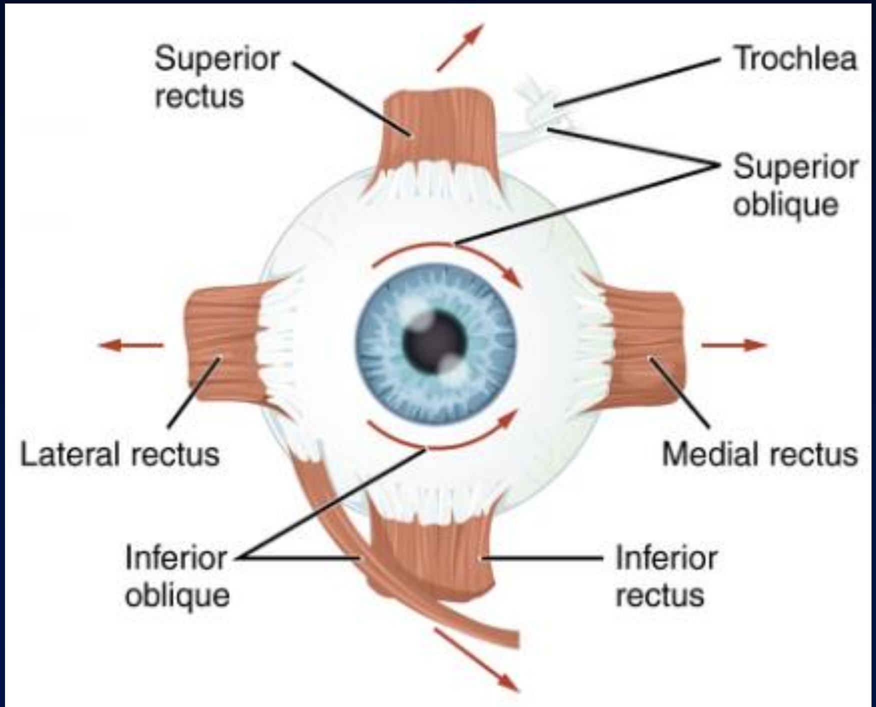
# Biomechanics of the Eye

## *Six extraocular eye muscles*



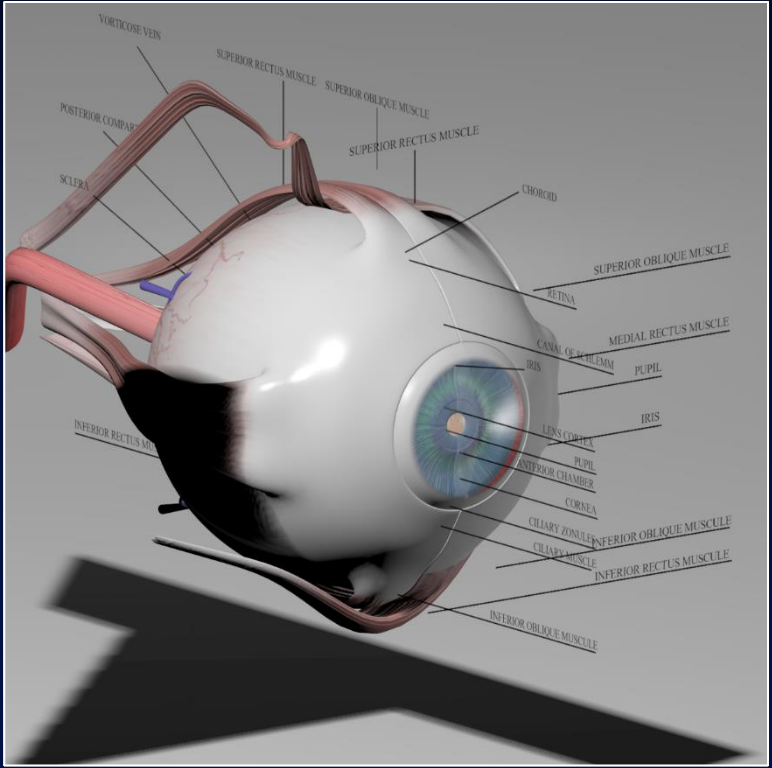

(a) Right eye (lateral view)

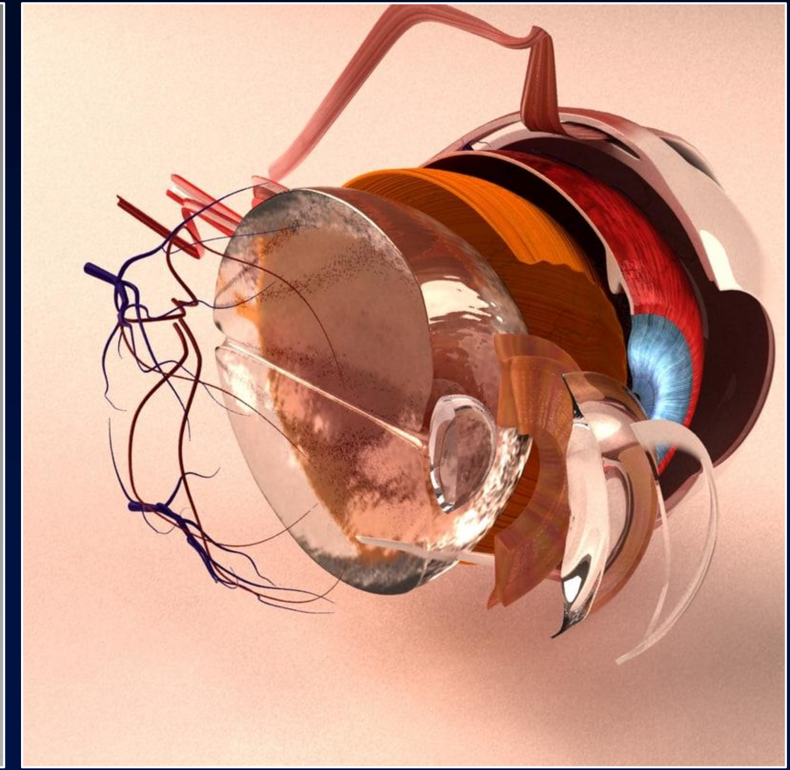
(b) Right eye (anterior view)

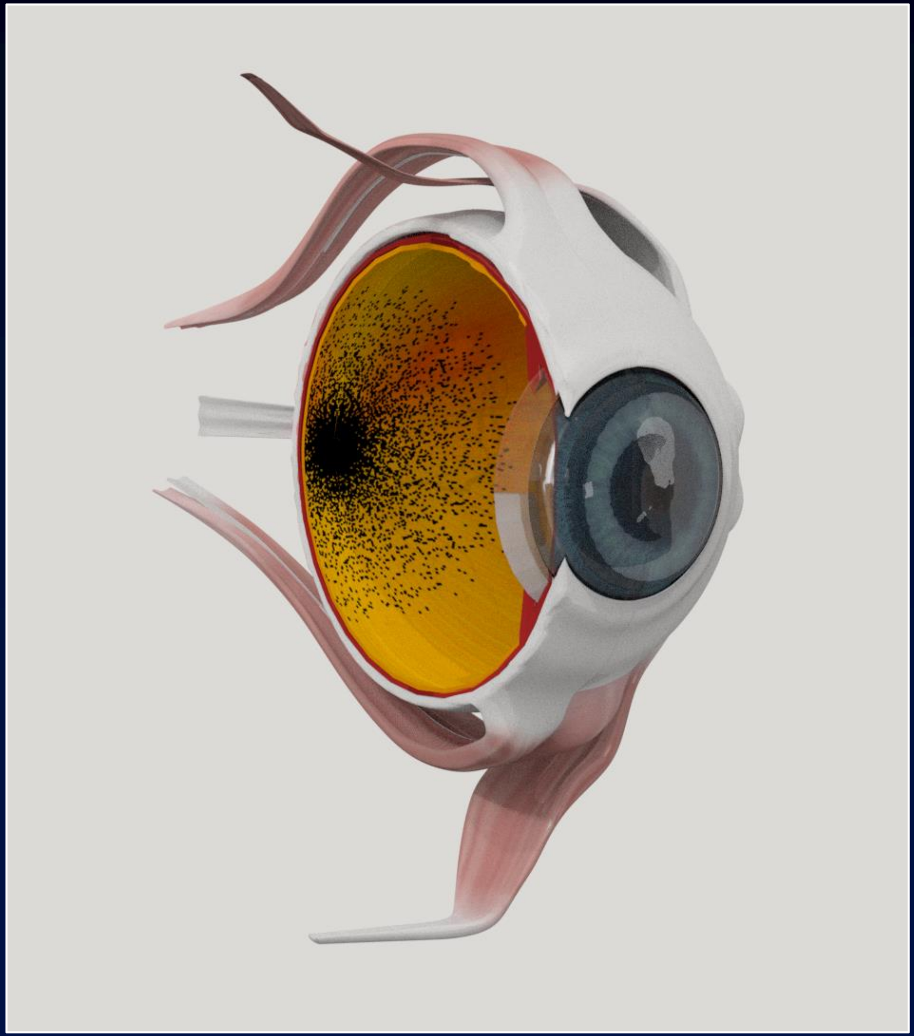


# A Detailed Eye Model

## *Muscles, cornea, iris, and lens*



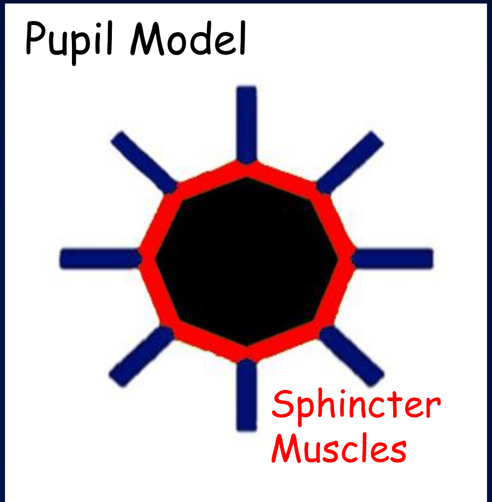



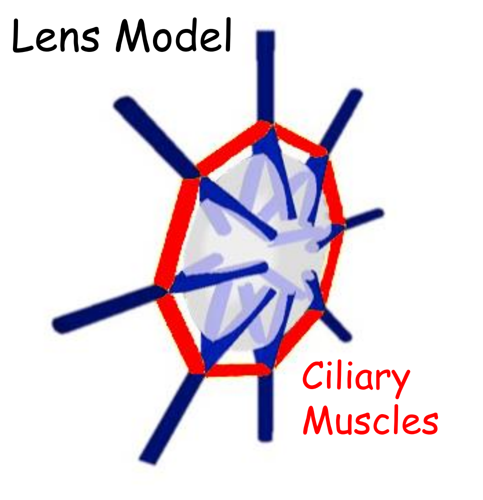


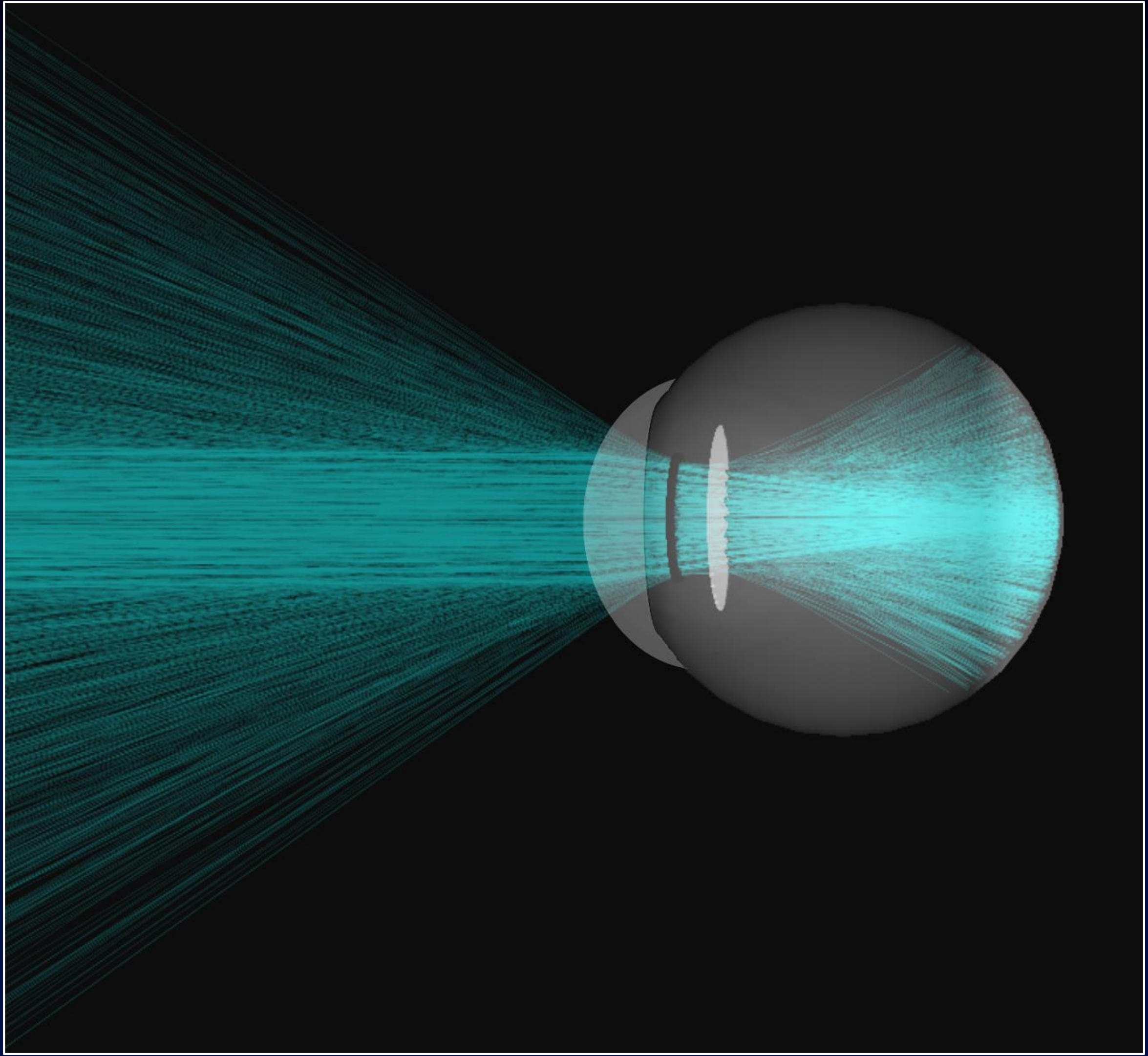
# Photoreceptor Irradiance Computation

## *Raytracing the ocular organs*

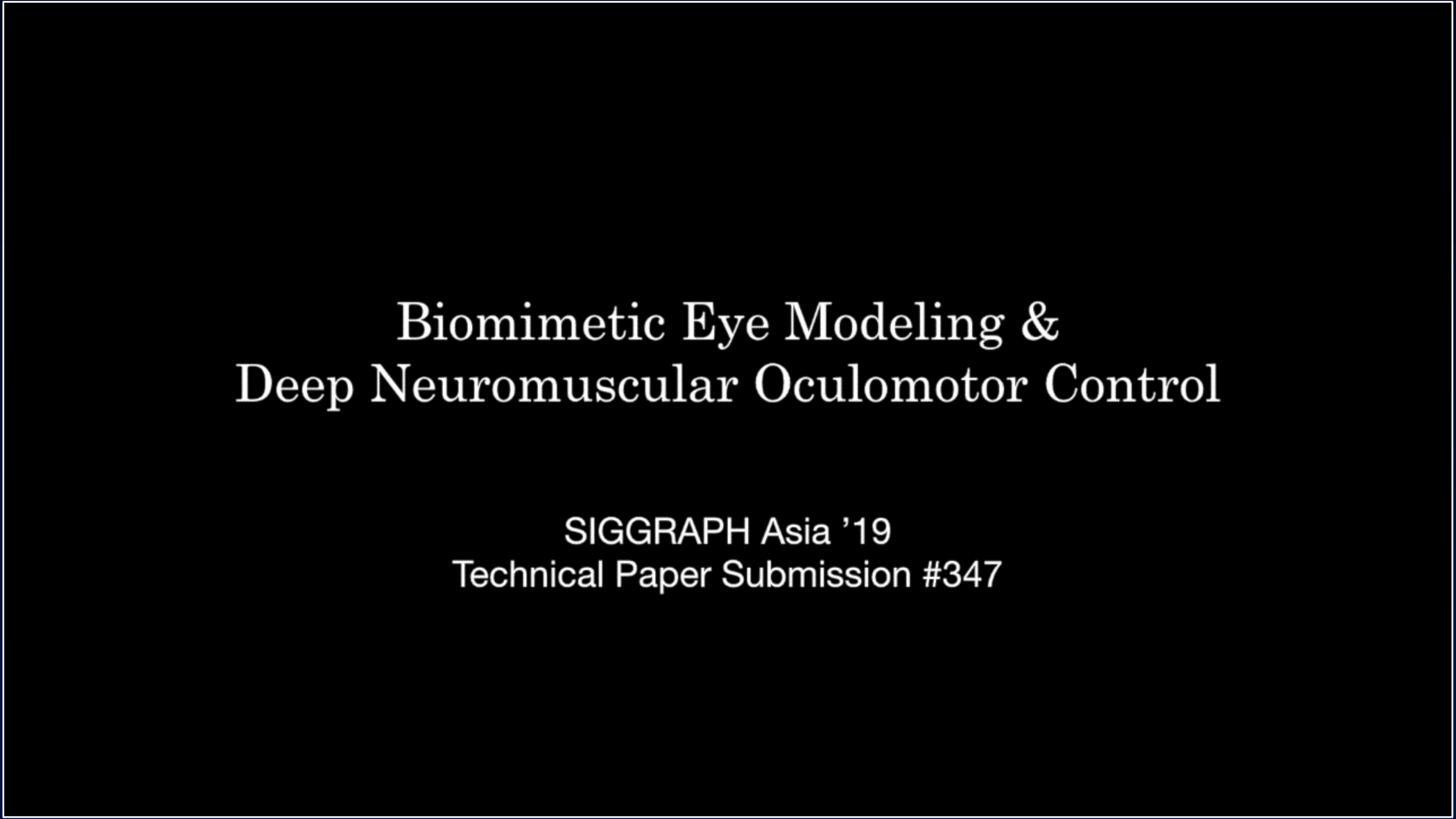
- Cornea refracts light rays
- Iris and finite-aperture pupil
- Deformable lens refracts rays



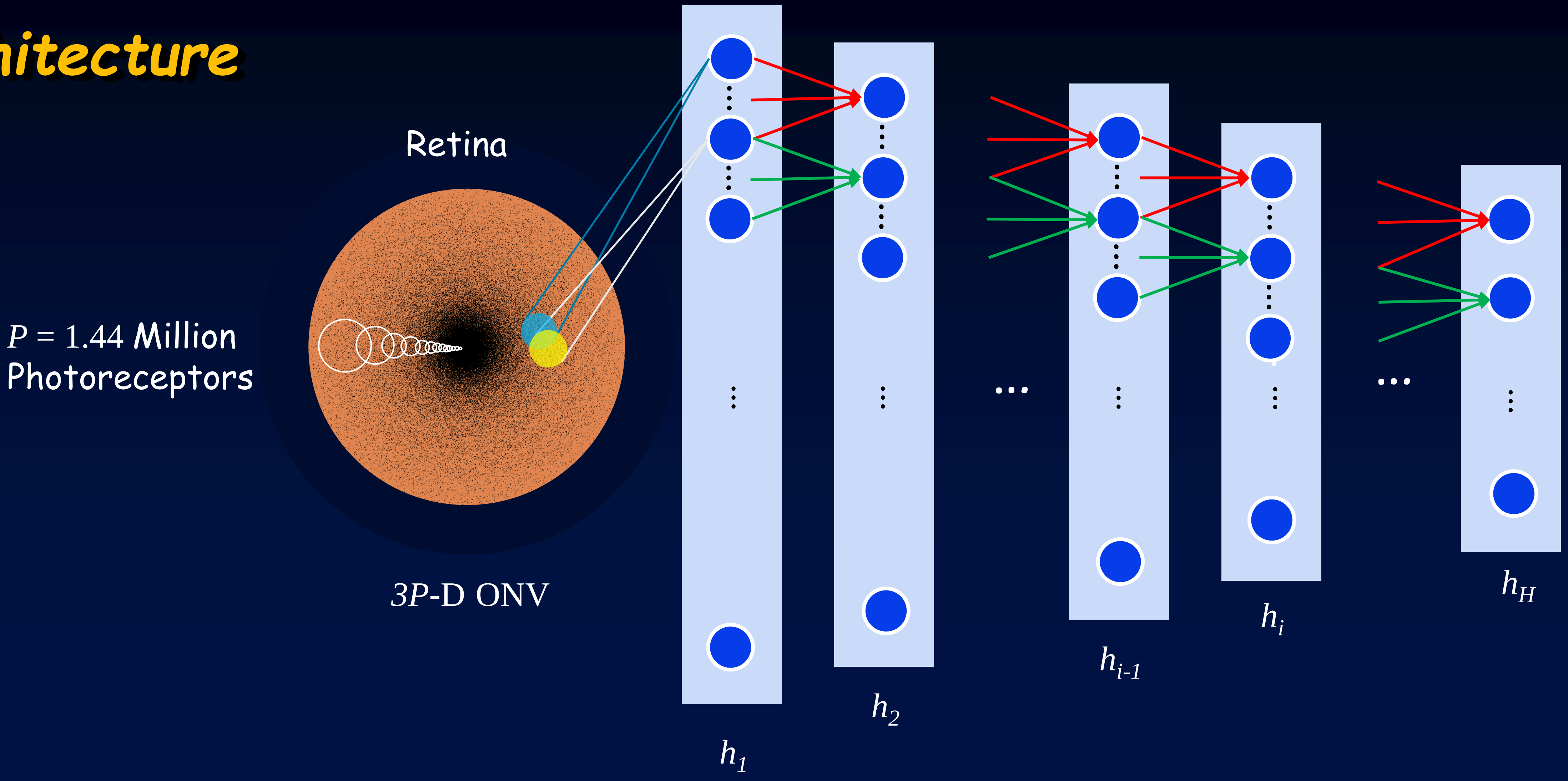



# Biomimetic Eye Modeling and Oculomotor Control



# Locally-Connected Irregular Network (liNet)

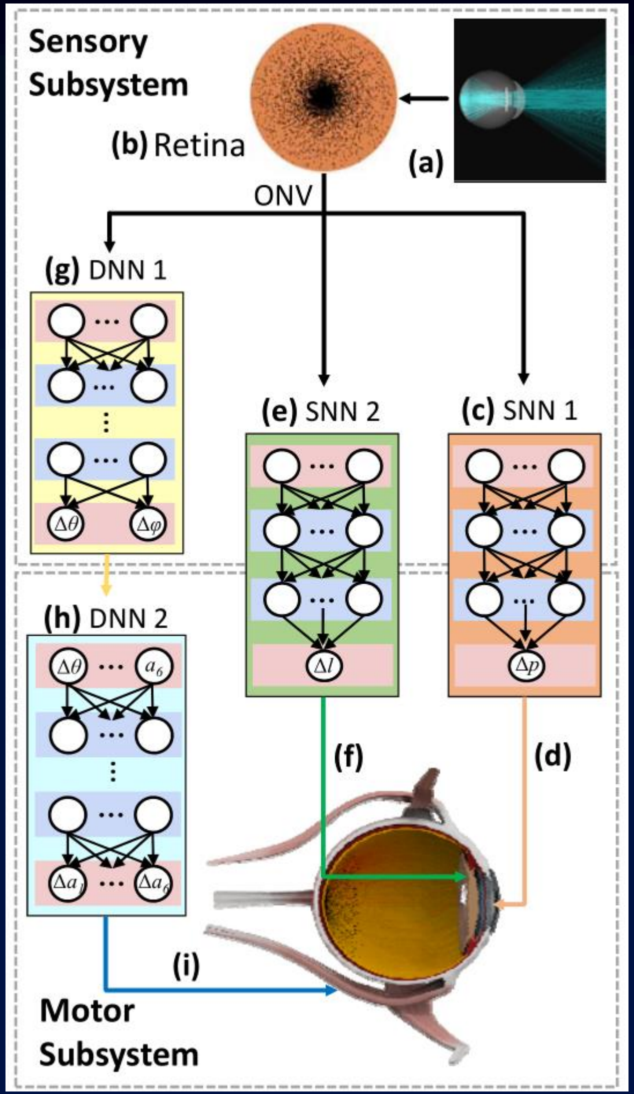
## Architecture



# Oculomotor Control System

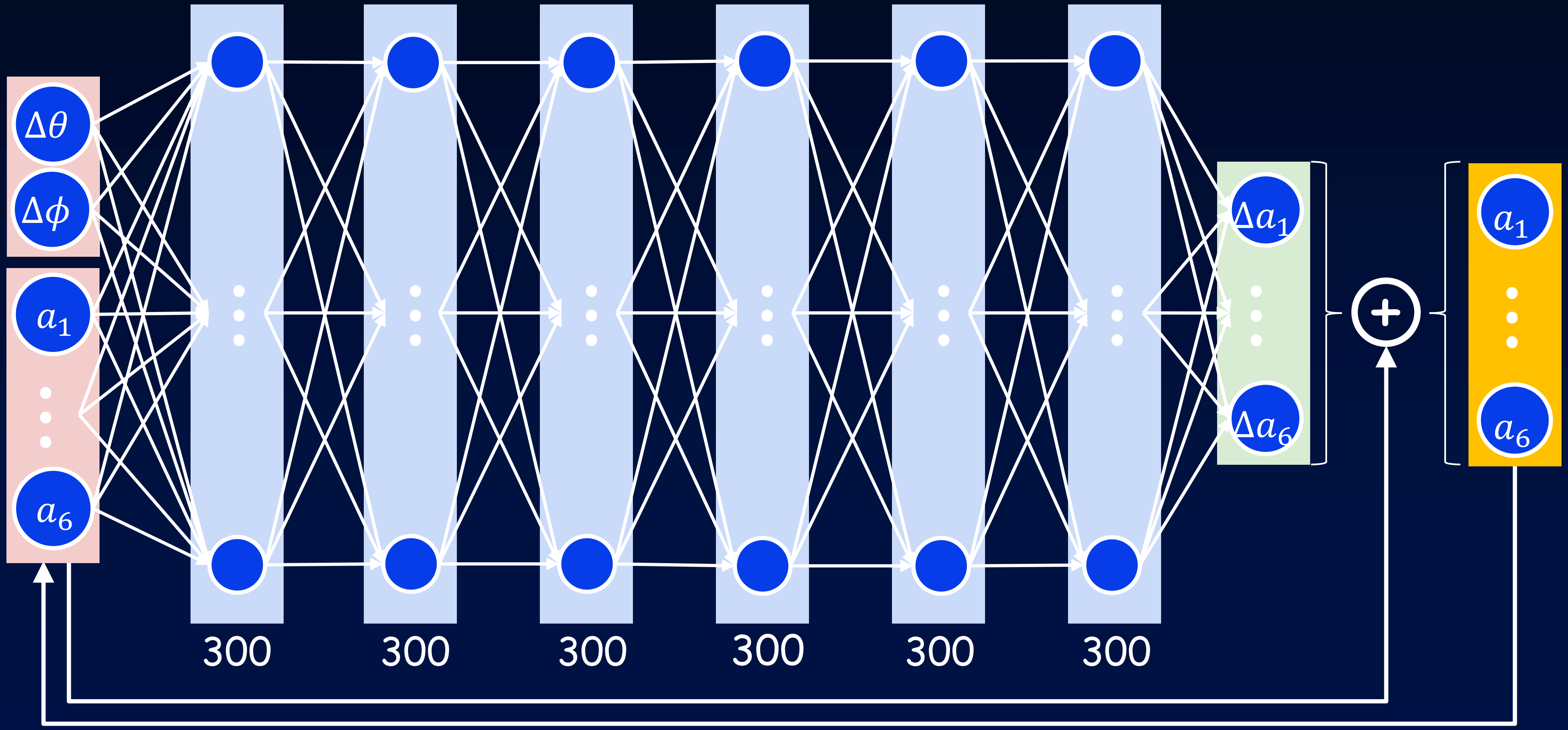
## *Architecture (per eye)*

- *1 vision DNN (foveation, smooth pursuit)*
- *1 motor DNN (eye movements)*
- *1 iris control SNN (luminance accommodation)*
- *1 lens control SNN (focal accommodation)*



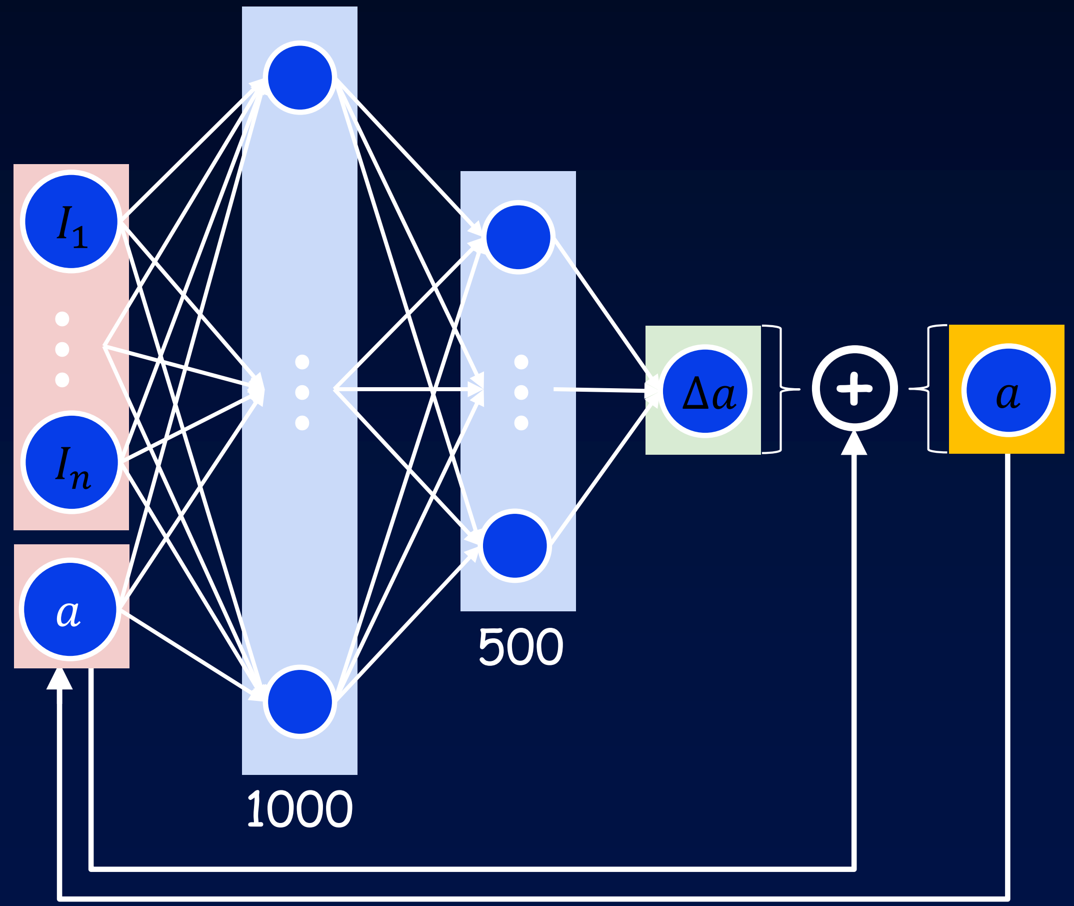
# Neuromuscular Motor Control DNN for the Extraocular Muscles (Eye Movements)

*Recurrent, 6-layer, fully-connected*



# Neuromuscular Motor Control SNN for the Intraocular Muscles (Iris Sphincter)

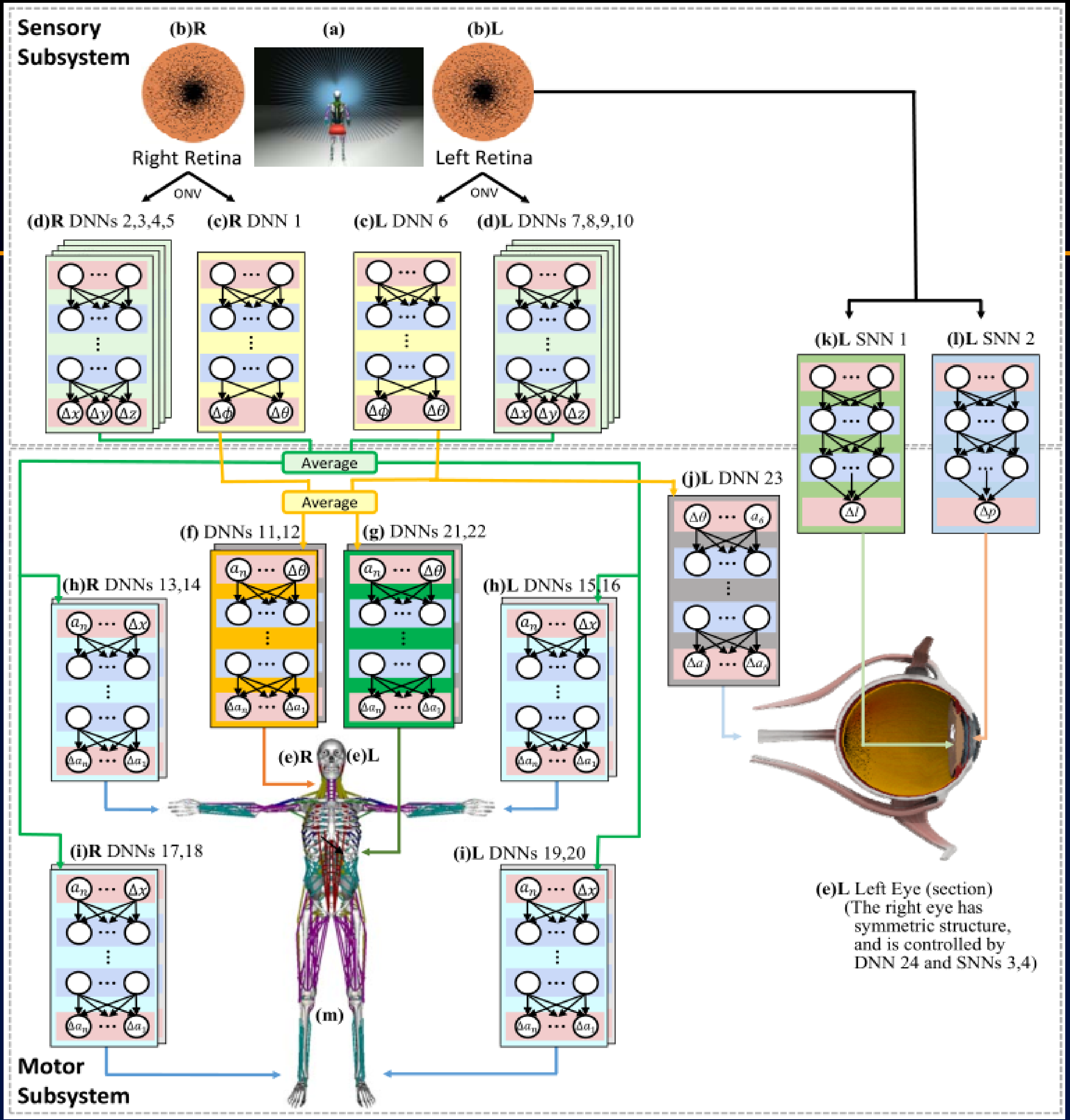
## *Recurrent, 2-layer, fully-connected*



# Current Sensorimotor System

## Architecture

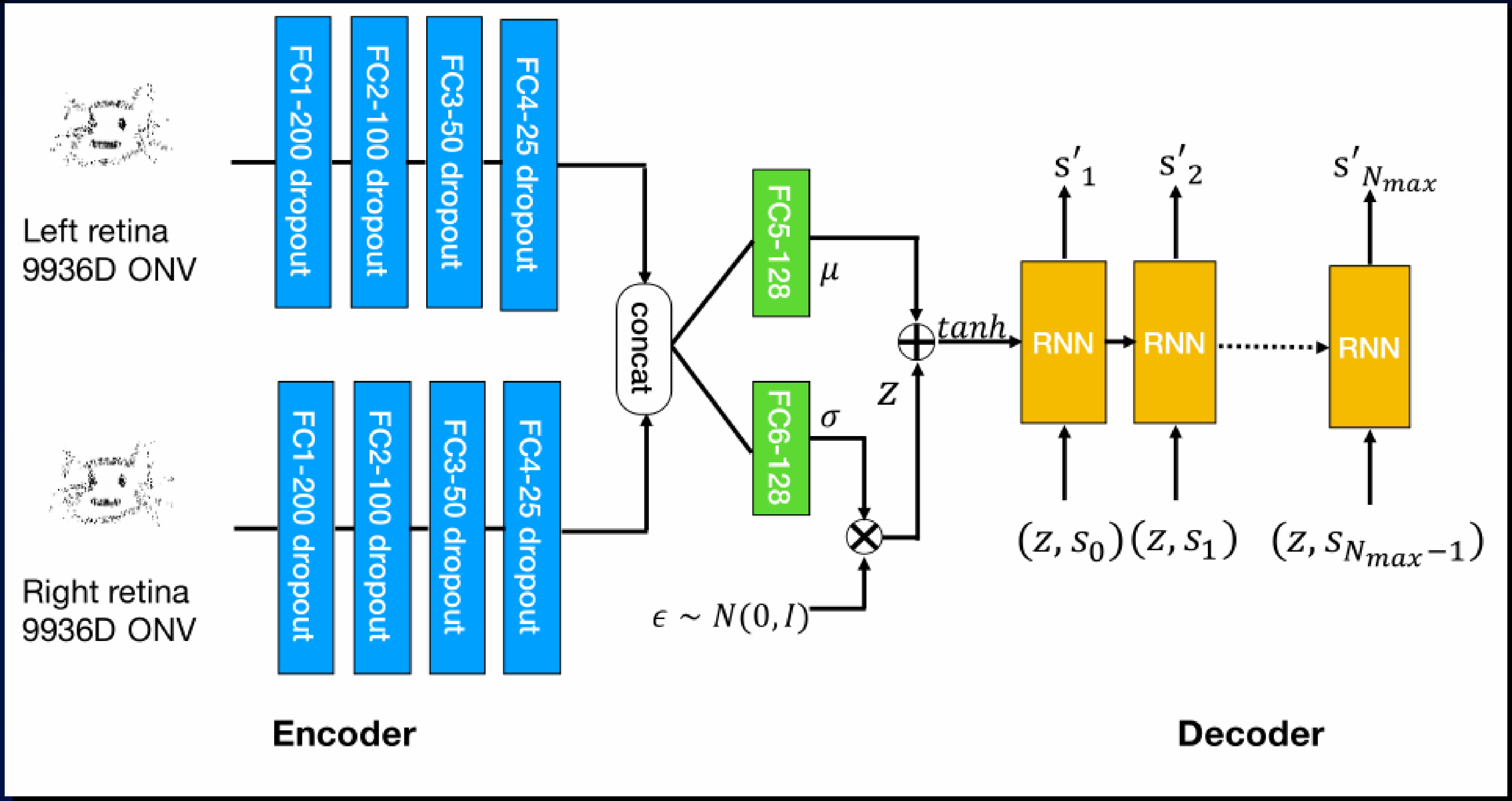
- 24 DNNs
- 4 SNNs



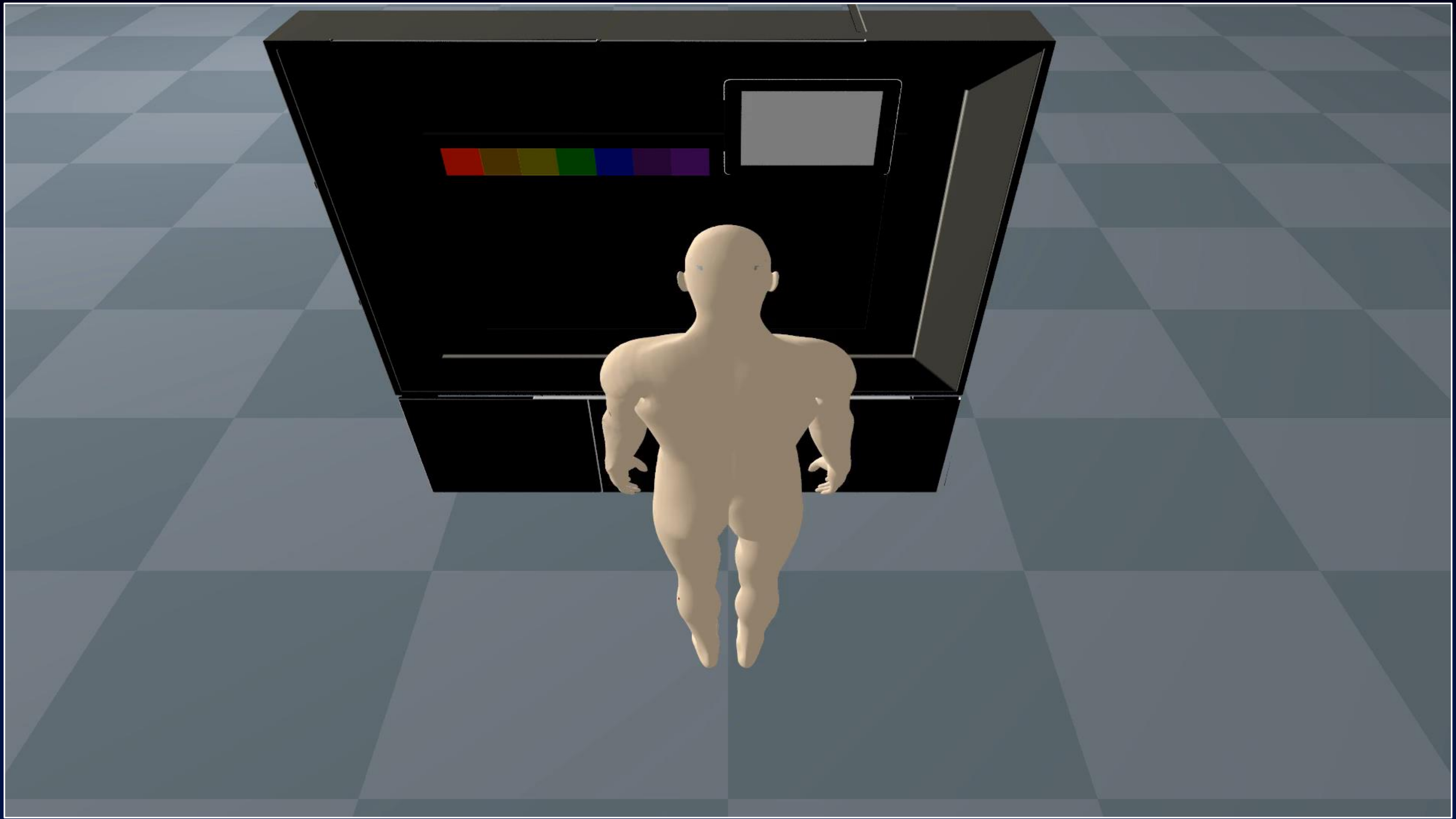
# A Higher-Level Vision System

## *Sketch analysis / synthesis with a recurrent NN model*

- Modified "Sketch-RNN"
  - *Encoder inputs: retinal photoreceptors*
  - *Decoder outputs: "pen" strokes*



# Sensorimotor Control: Sketching



# Acknowledgements

## *My students whose work was presented*

### *PhD Students:*

| | | |
|---|---|---|
| Sung-Hee Lee | (KAIST) | - human body modeling and cervicocephalic control learning |
| Justin Si | (Facebook) | - swimming simulation and CPG control |
| Masaki Nakada | (NeuralX) | - deep learning of neuromuscular and sensorimotor control |
| Tao Zhou | (UCLA) | - deep learning of neuromuscular torso control |

### *MS students:*

| | | |
|---|---|---|
| Arjun Laksmipathy | (CMU) | - biomechanical eye modeling and neuromuscular control |
| Yuenchen Lee | (Monestary) | - facial modeling and animation |

### *BS student:*

| | | |
|---|---|---|
| Honglin Chen | (Stanford) | - liNets and biomimetic perceptual modeling |

### *Postdoc:*

| | | |
|---|---|---|
| Eftychios Sifakis | (U Wisconsin) | - body soft tissue simulation and surgery simulation |

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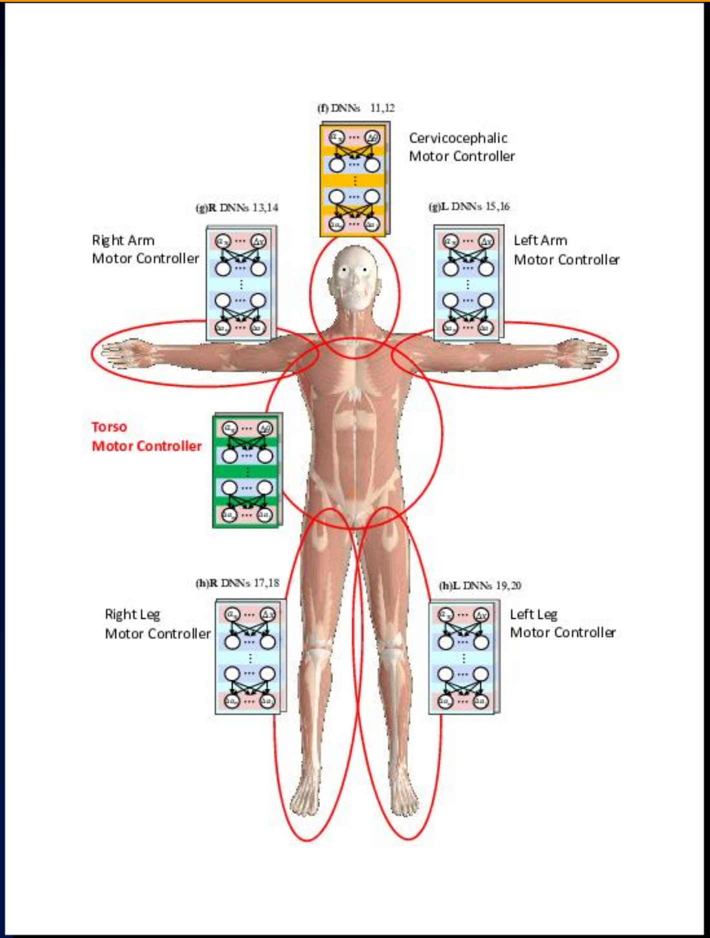
# Thank You !

Terzopoulos.com


(f) DNNs 11,12
Cervicocephalic
Motor Controller
(g)R DNNs 13,14
Right Arm
Motor Controller
(g)L DNNs 15,16
Left Arm
Motor Controller
Torso
Motor Controller
(h)R DNNs 17,18
Right Leg
Motor Controller
(h)L DNNs 19,20
Left Leg
Motor Controller