Modelling and Simulation

Introduction

Course plan

- Course time: Monday 09:00 – 11:00
- Lectures – Lab (Room? Equipment?):
  - #1 Theory 1 – Introduction
  - #2 Theory 2 – Transformations
  - #3 Theory 3 – Lagrangian Dynamics
  - #4 Theory 4 – Kinematics / Dymanics
  - #5 Lab 1 – Simple dynamics
  - #6 Lab 2 – Arm dynamics
  - #7 Lab 3 – OpenSim introductionTheory
  - #8 Projects
  - #9 Theory 5 – Inverse Simulation
  - #10 Lab 4 – Inverse Simulation
  - #11 Theory 6 – Forward Simulation
  - #12 Lab 5 – Forward simulation
  - #13 Projects – VPH extrapolation

Why?

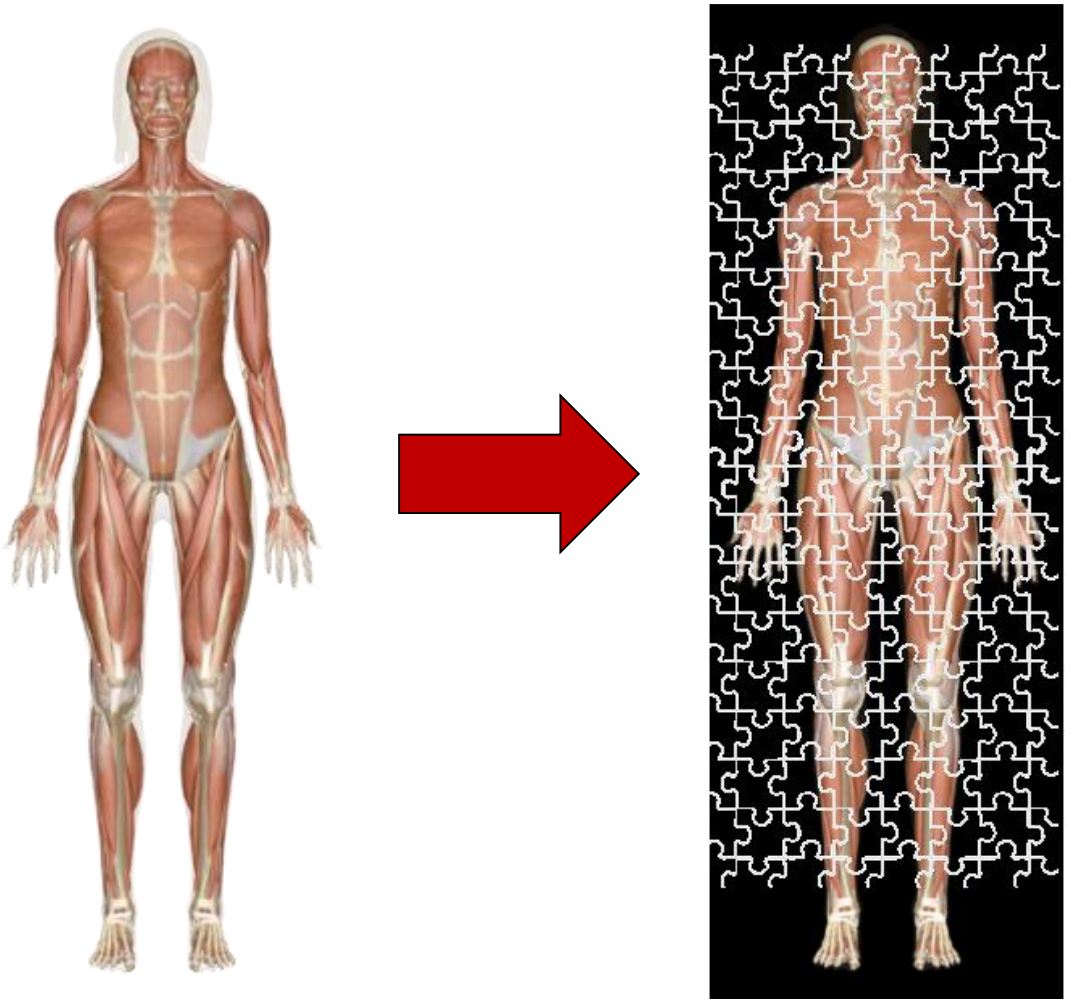
- How can we better understand life?

Introductory parts of this lecture is inspired by Marco Viceconti's talk at TeDx-Sheffield

One huge problem → Complexity

How to deal with this problem?

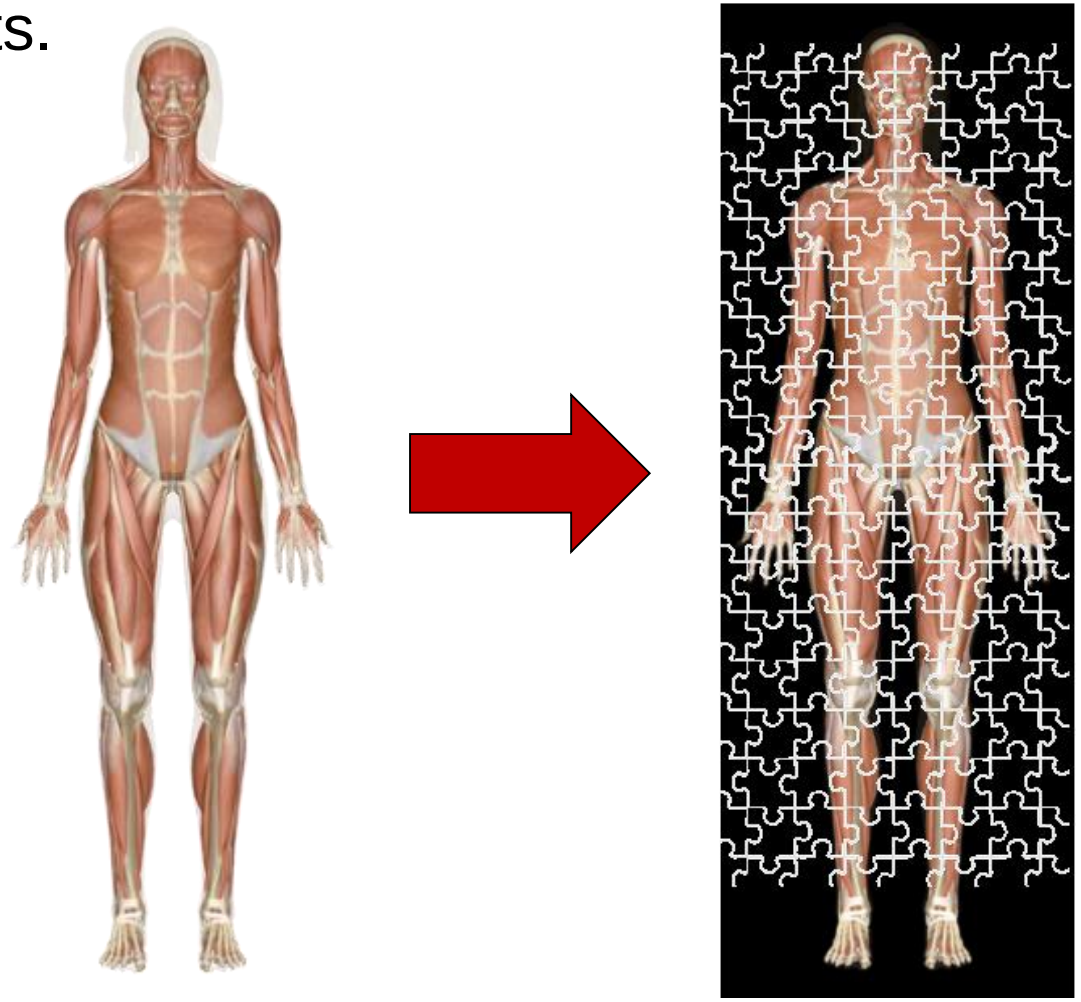
- Divide and conquer → Reductionism



- This is what medicine does for the last 2000+ years…

Reductionism

- Hierarchical decomposition into parts. Parts → subparts → subsubparts.



- Then deal with each minor part PRETENDING that each part is independent

Why?

- And… how surprising it WORKED
- Our understanding on the human body increased together with our ability to heal diseases
- But as every thery it works until it does not
- We are in such a position today!
- Let us check four diseases that have severy socioeconomic impact to the society
  - Cardiovascular
  - Cancer
  - Diabetes
  - Osteoporosis
- Very little in common except one thing
  - Cannot be explained by looking only at a single part of the body

Why?

- Very little in common except one thing
  - Cannot be explained by looking only at a single part of the body

Why?

- Example of an elderly person: osteoporosis, visual impairement, week muscles, probability of falling...

- How can we treat this issue by looking only at specific organs.

- Two of the most important conditions in the EU today are falls and frailty... Global conditions

Why?

- However reductionism is still popular→ If we go down and down to the DNA then everything can be solved magically, since the signature of every organ is coded in the DNA

- https://www.youtube.com/watch?v=wxRHZ4D0zJk

Why?

- Experiment of applying a presure on the hand to modify the production of proteins of a specific cell→ DNA is an important but not sole controller!!!

Why?

- But how to deal with such a complexity if not considering reductionism as our only tool?
- Computer simulations!
- Practically
  - Take the knowledge that has been produced for the human body
  - Express it in mathematical terms
  - Produce computer programs that simulate its behavior under specific conditions
- Multi-scale
  - Human body
  - Organ
  - Tissue
  - Cell
  - Molecule
- Interaction among levels

Why?

- So what???
- One more important issue to deal with
  - Personalization → patient specific modeling
- Example of the VPH video on how things could be in the future…
- VPH → the future
- Not so far away → Electronic health records
- Examples
  - Lung→ myAirCoach
  - Eyes → NoTremor
  - Arm → NoTremor
  -

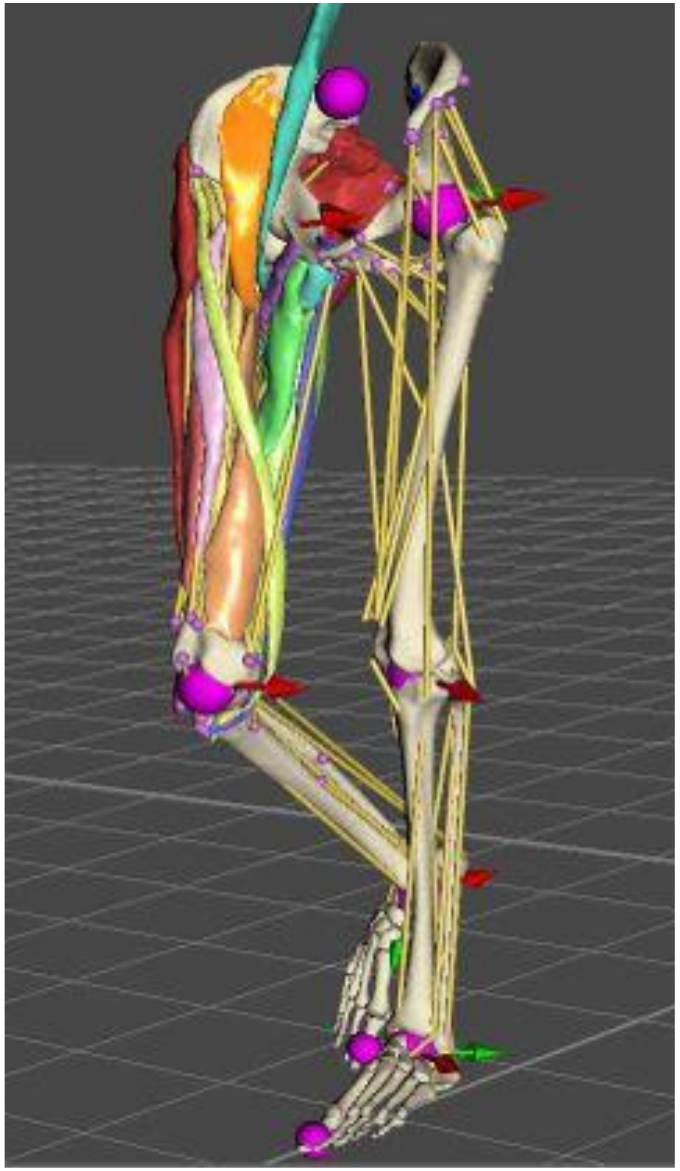
Why?

Virtual Physiological Human

- The human body is like a jigsaw puzzle made of a trillion pieces.
- Currently we try to understand the whole picture by looking at a single piece, or at a few closely inter-connected pieces.
- The Virtual Physiological Human is the frame within which we can finally start to place the pieces all together, and the glue that connect them.

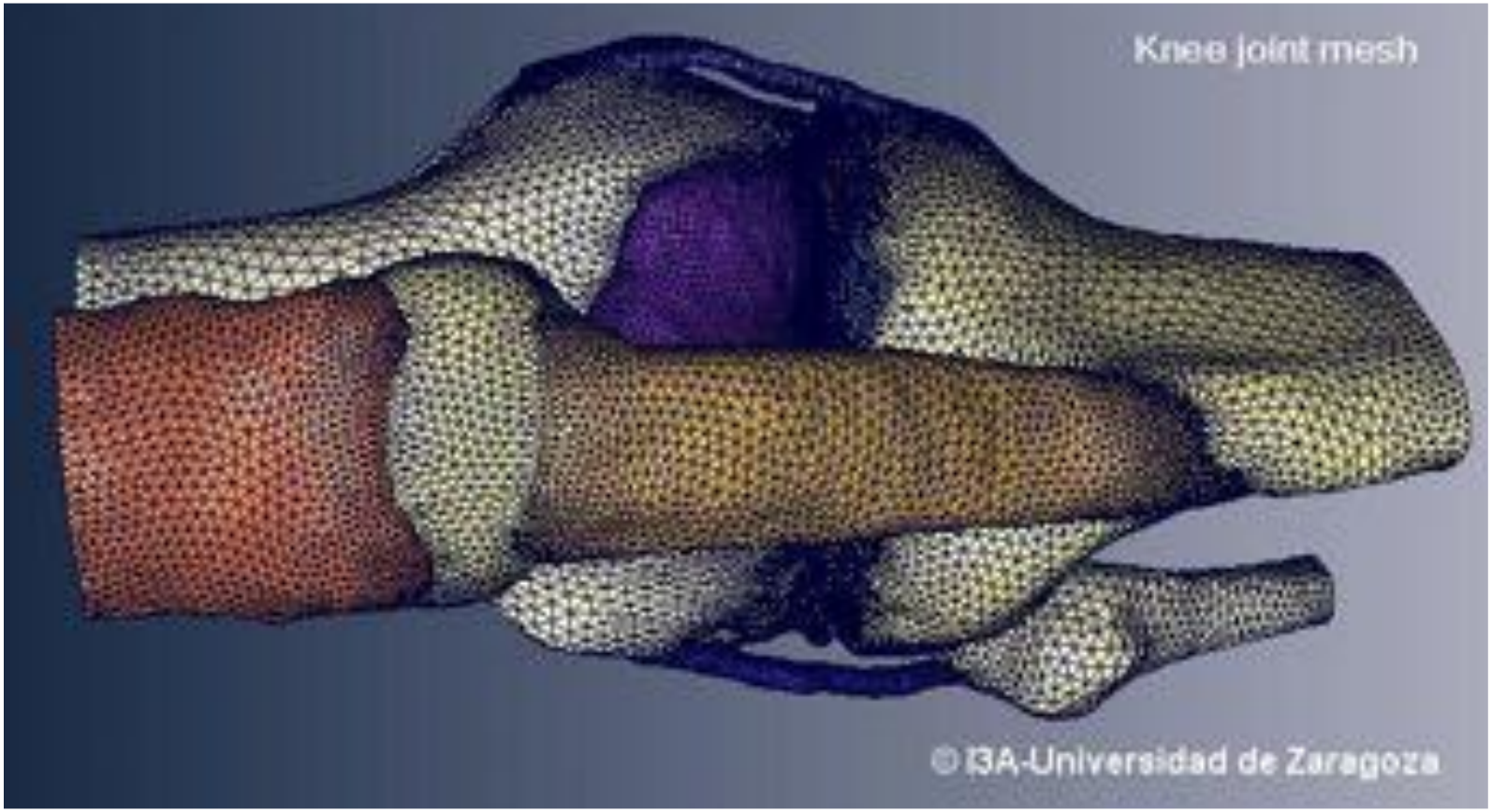
- Where do Diagnosis & Treatment fit on the above?

Modeling

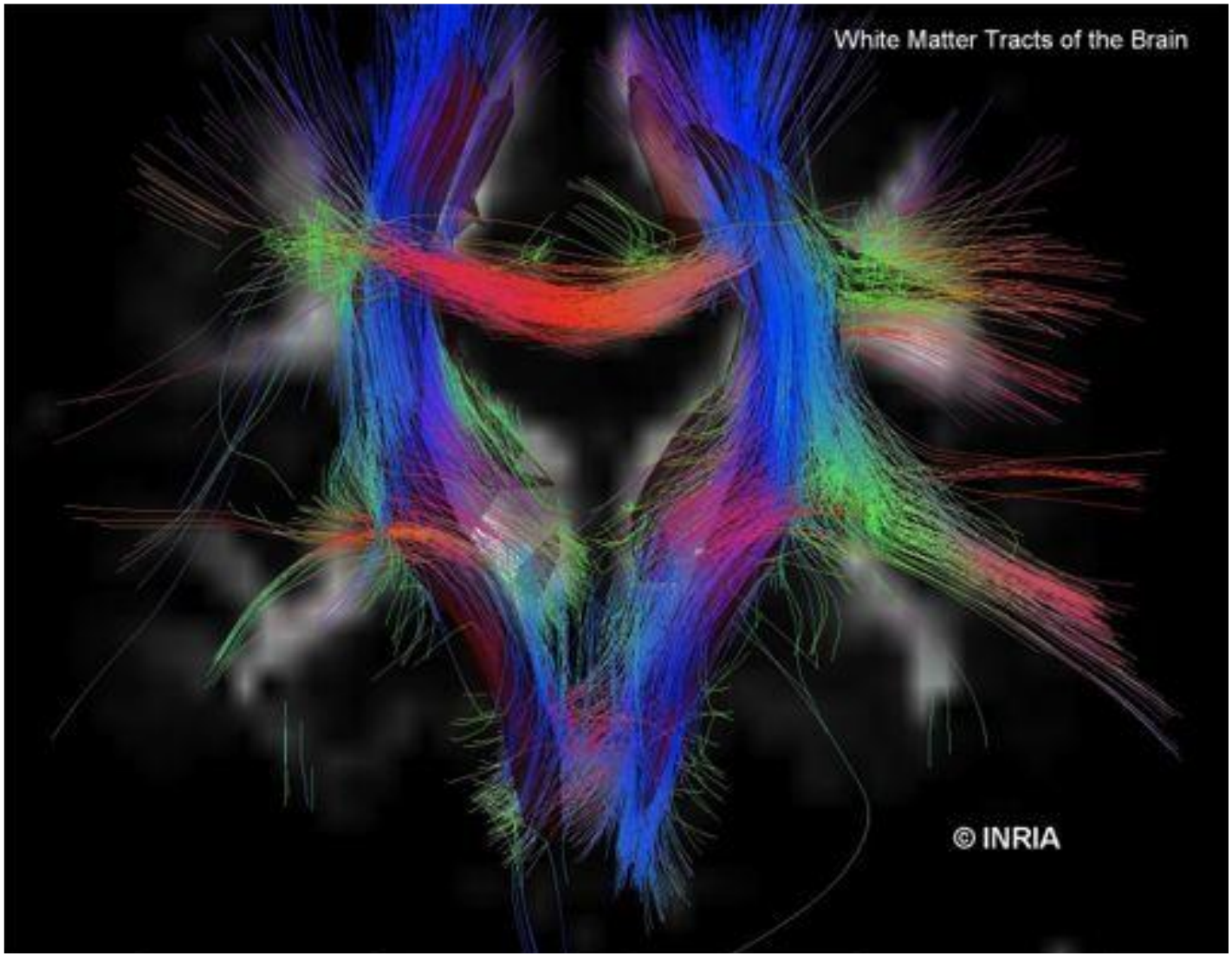


Modeling

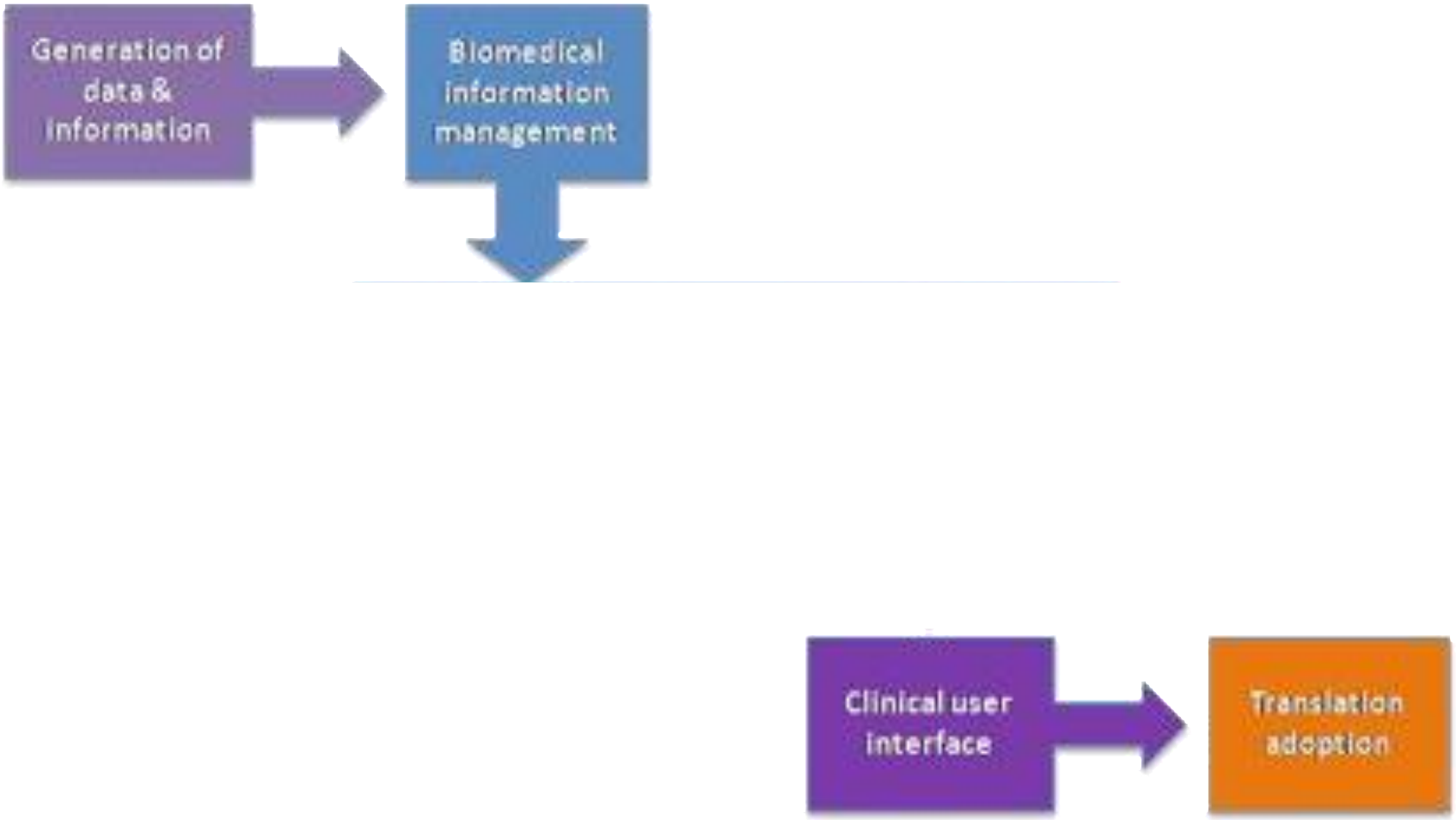
Data



Data



Virtual Physiological Human



Levels of modeling

Modeling levels

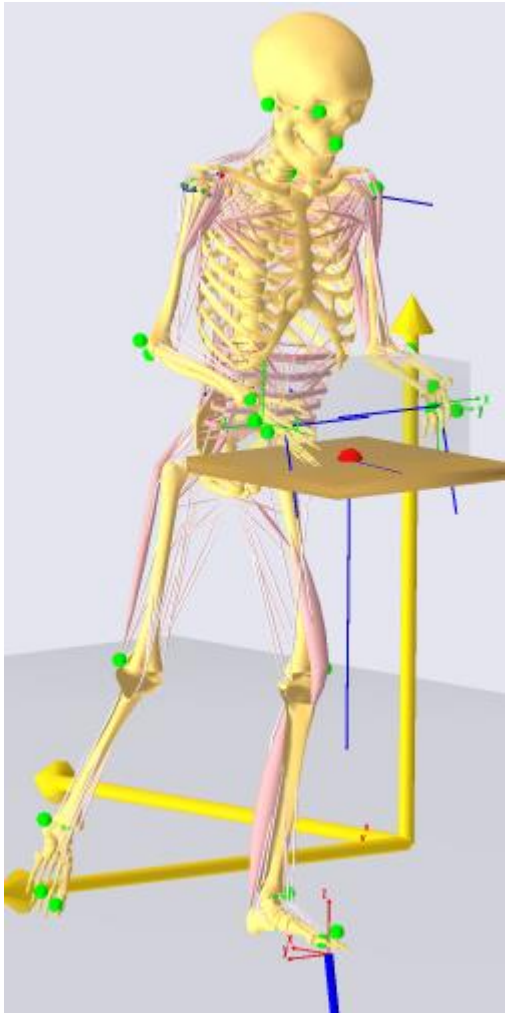
- *Cellular level*
- *Molecular level*
- *Organ level*
- *System Level*
- *Full-scale body level*
  - *Neuromusculoskeletal level*

What is a virtual human?

- *Is this a virtual human?*

What is a virtual human?

- *Is this a virtual human?*



Virtual humans

- *Their properties?*
  - *Perceiving entity*
  - *Actuating*
  - *Autonomous*
  - *Mimics life*
  - *…*
  - *…*
  - *…*
  - *…*
  - *…*

Virtual humans

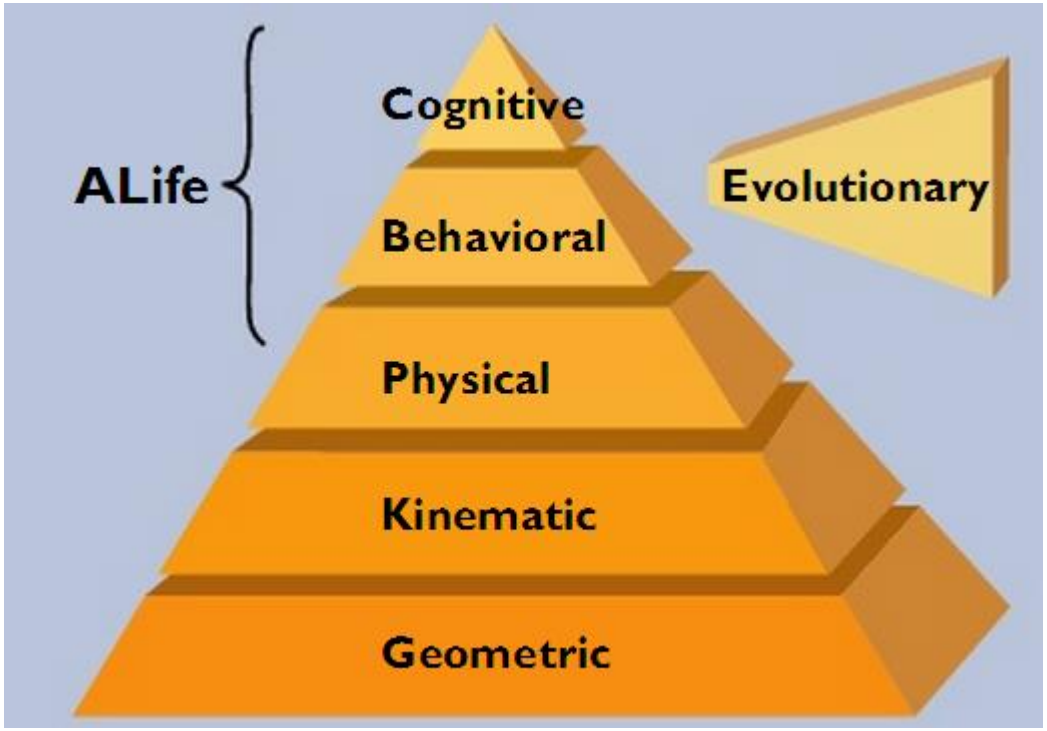
- *Sensors*
  - *Virtual cameras*
  - *Force sensors*
  - *…*
- *Actuators*
  - *Virtual muscles*
  - *Wheels*
  - *…*
- *Controllers based on*
  - *Kinematics*
  - *Dynamics*
  - *… + Physics*

Humans vs. Virtual Humans

- *Differences?*
  - *Physics*
  - *Time*
  - *Lives in the virtual world with a virtual clock!*
  - *What is “real-time”?*

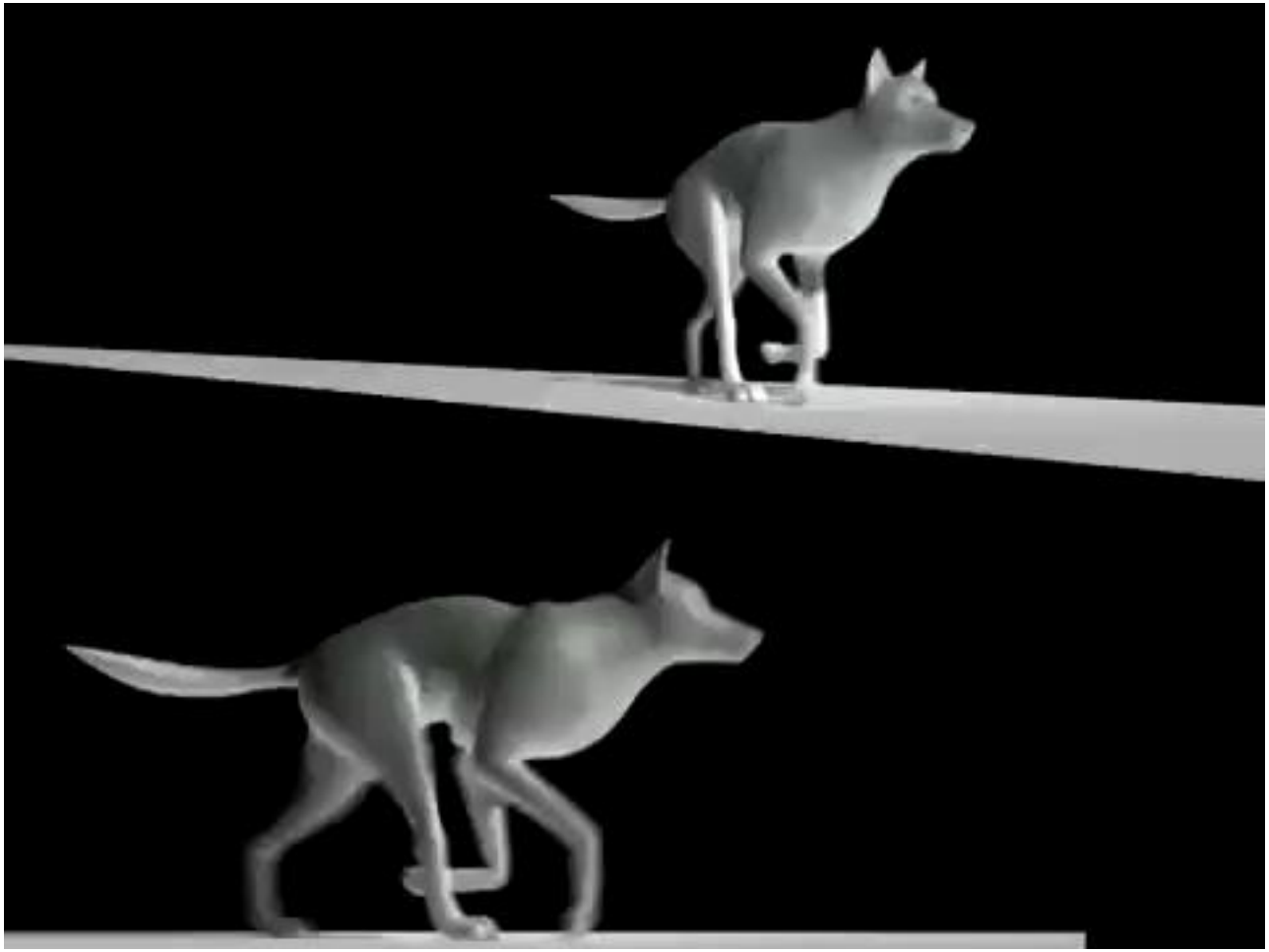
Life pyramid

- *D. Terzopoulos, Artificial Life…*



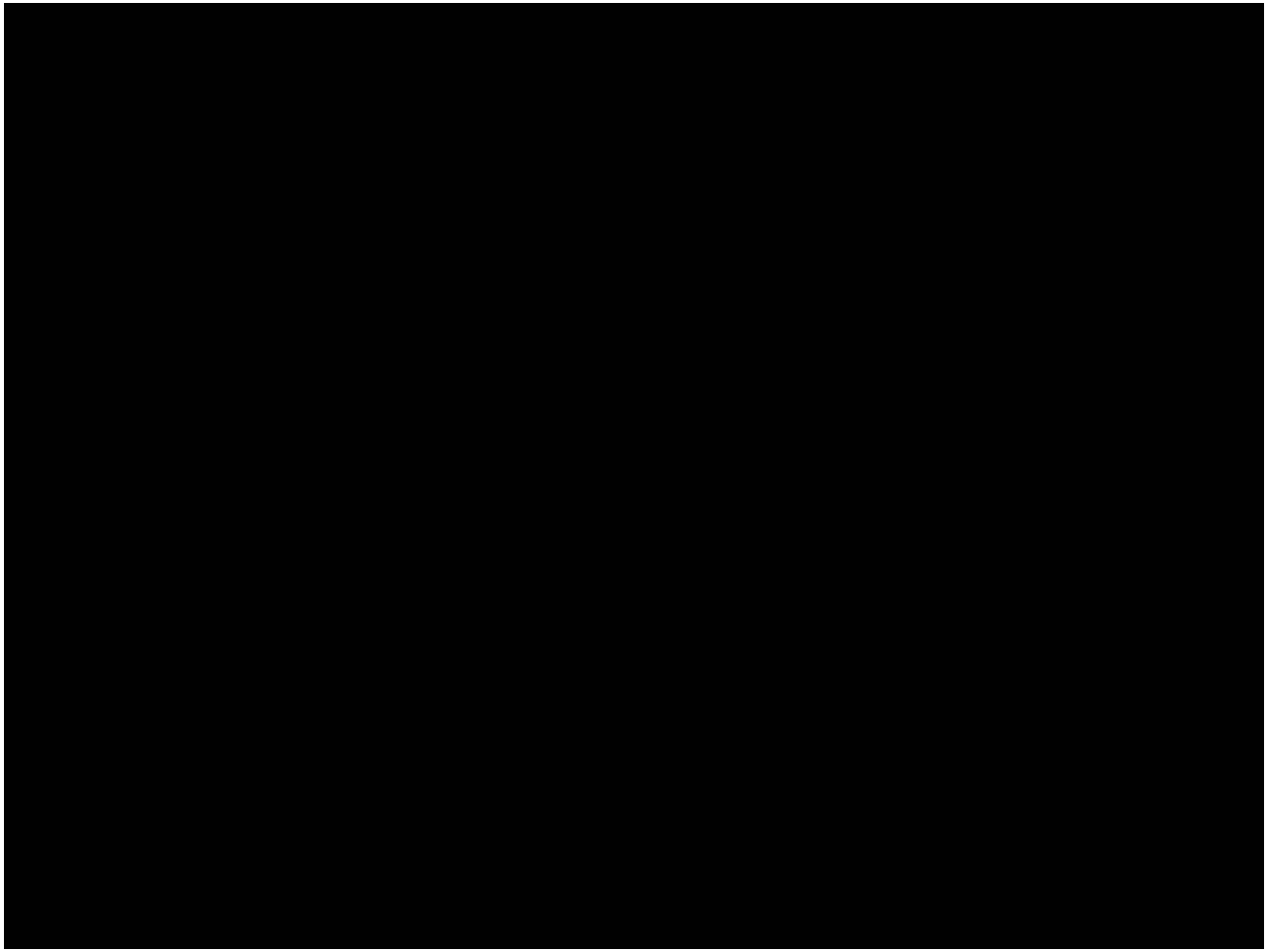
What is a virtual animal?

- *Is this a virtual animal?*



What is a virtual human?

- *Is this a virtual human?*



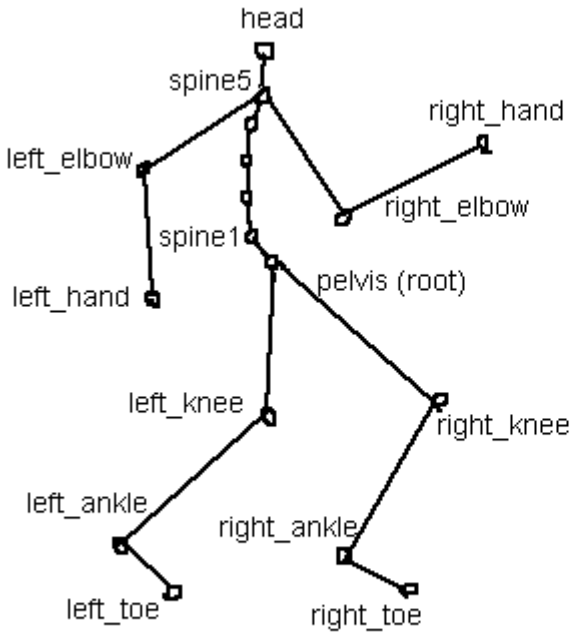
Is this a virtual creature?

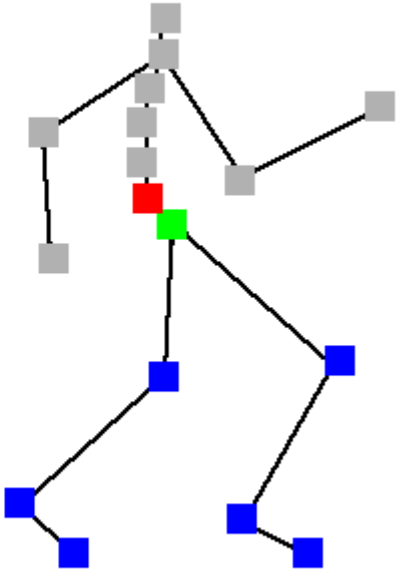
- *Is this a virtual creature in the VPH sense?*

Virtual Humans

- *Animation vs. Simulation*

Animation





- Keyframe based animation
- Keyframes manually edited
- Alternative: motion tracking

- Skeletal motion applied to skin

Simulation

- *Definition of physical laws*
  - *Gravity*
  - *…*
- *Definition of physical properties*
  - *Mass*
  - *Elasticity*
  - *…*
- *Definition of simulation-specific quantities*
  - *Viscosity*
  - *Constraints*
  - *…*

$$\underbrace{M\ddot{u} + \left(\alpha M + \beta K(u) + D\right)\dot{u} + f_{\text{int}}(u) = f_{\text{ext}}}_{M\gamma = \Sigma F}$$

Now what???

$$\dot{\mathbf{u}}_i^{n+1} = \dot{\mathbf{u}}_i^n + \mathbf{F}_i^n \frac{dt}{m_i}$$

$$\underbrace{\mathbf{u}_i^{n+1} = \mathbf{u}_i^n + \dot{\mathbf{u}}_i^n dt}_{\text{Numerical integration (Timestepping)}}$$

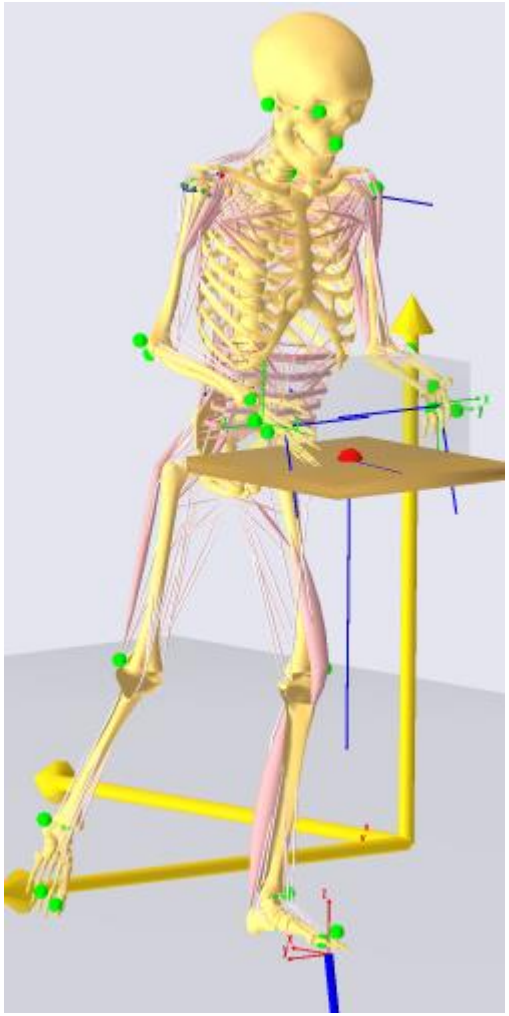
Applications in medicine

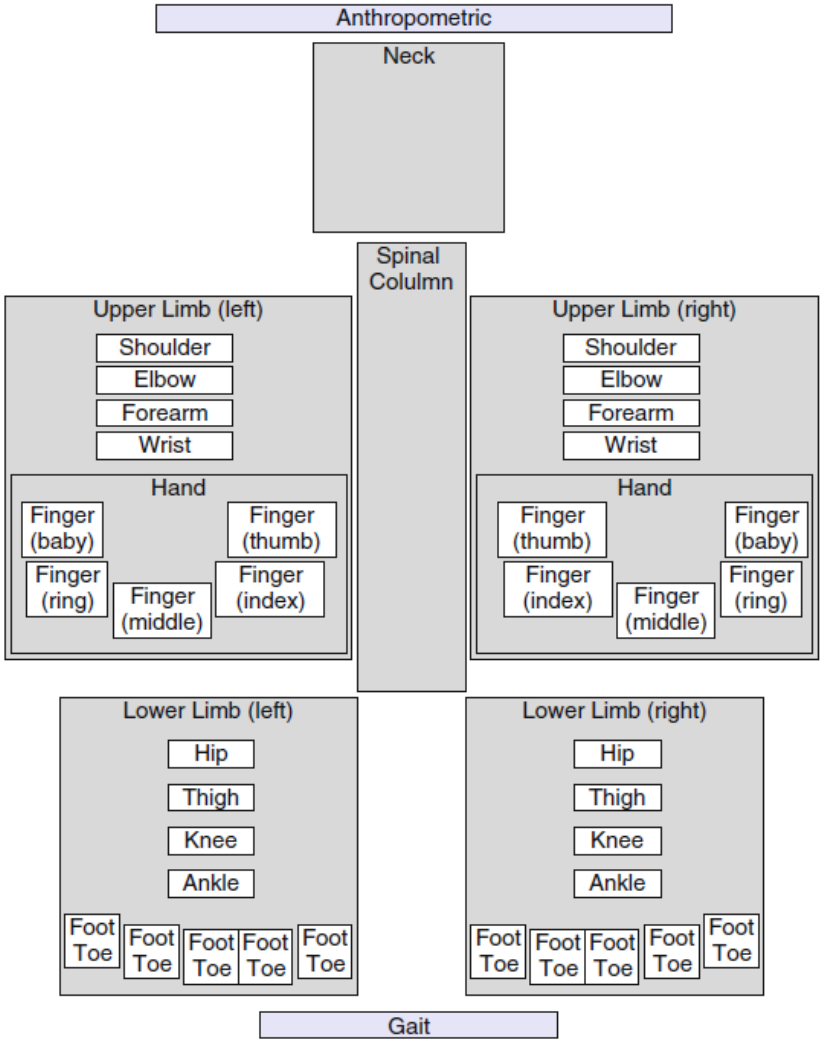
- ***Accessibility engineering***
  - **Without simulation**: Testing products, software with real patients
  - **With simulation**: Testing products in a virtual prototyping step with virtual humans
- ***Virtual physiological humans***
  - Virtual humans that replicate human physiology, useful for:
  - Drug discovery
  - Personalized treatment (pharmaceutical, surgical, etc.)
  - Medical research…

Simulated ergonomics/accessibility

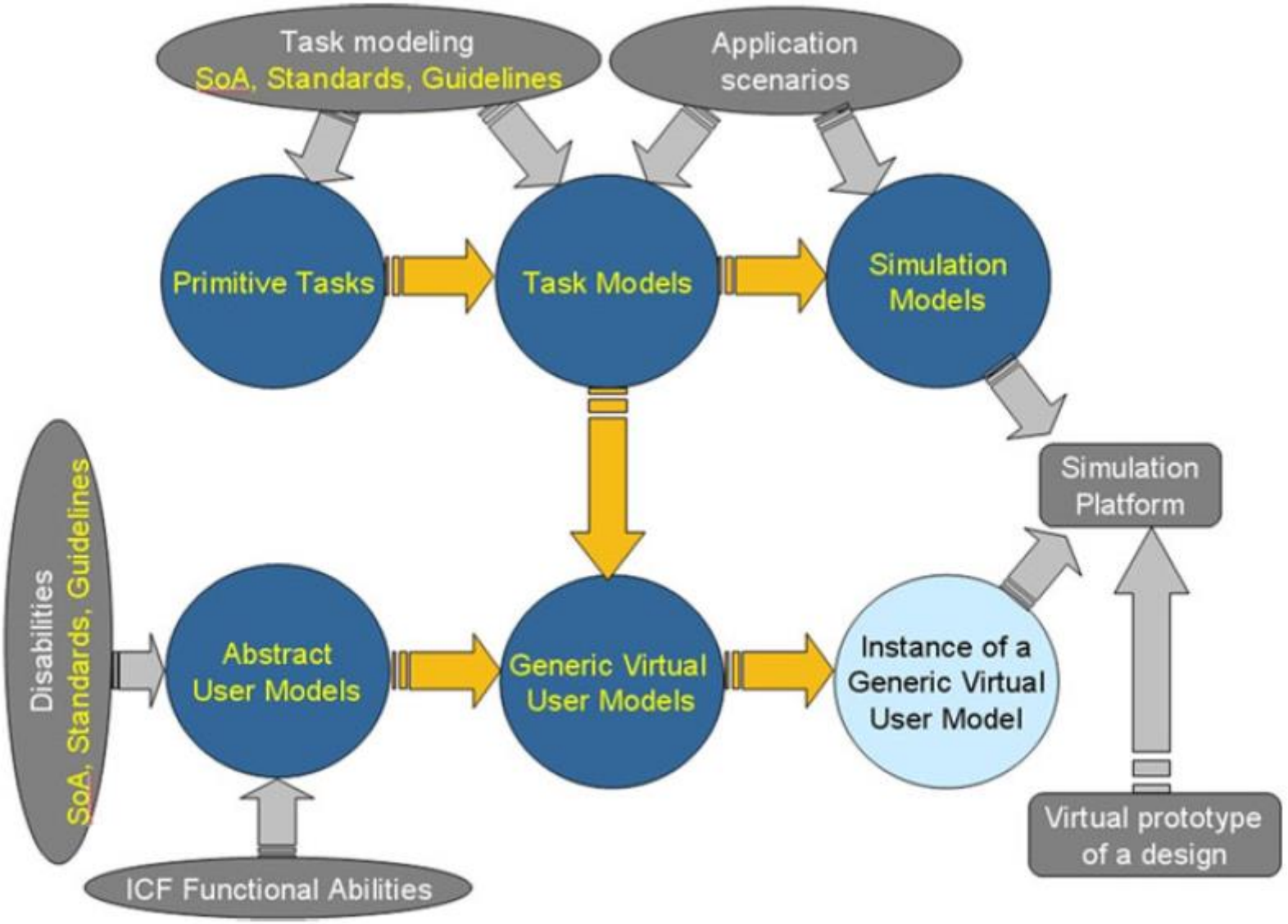
- *Motivation:*
  - *Analyze the design of products in terms of its ergonomy/accessibility in a virtual prototyping step*
- *State-of-the-art solutions*
  - *Real prototype*
  - *Real test with users/disabled*
  - *Expensive, time consuming*
  - *Manual kinematics*
- *Simulation based solutions*
  - *Simulated accessibility/ergonomy evaluation*
  - *Physiological human modeling*
  - *VPH simulation*

User model example

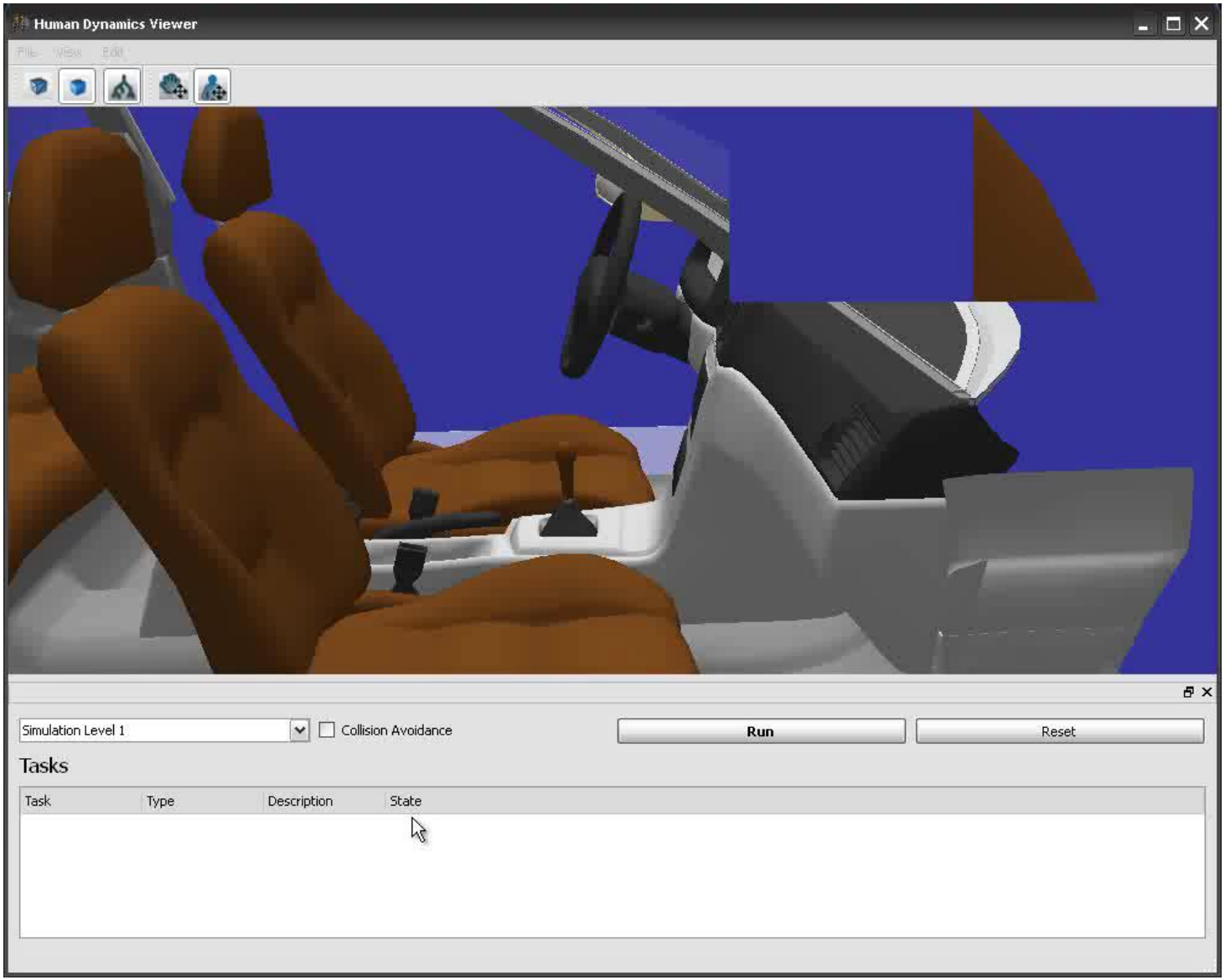




Simulation methodology

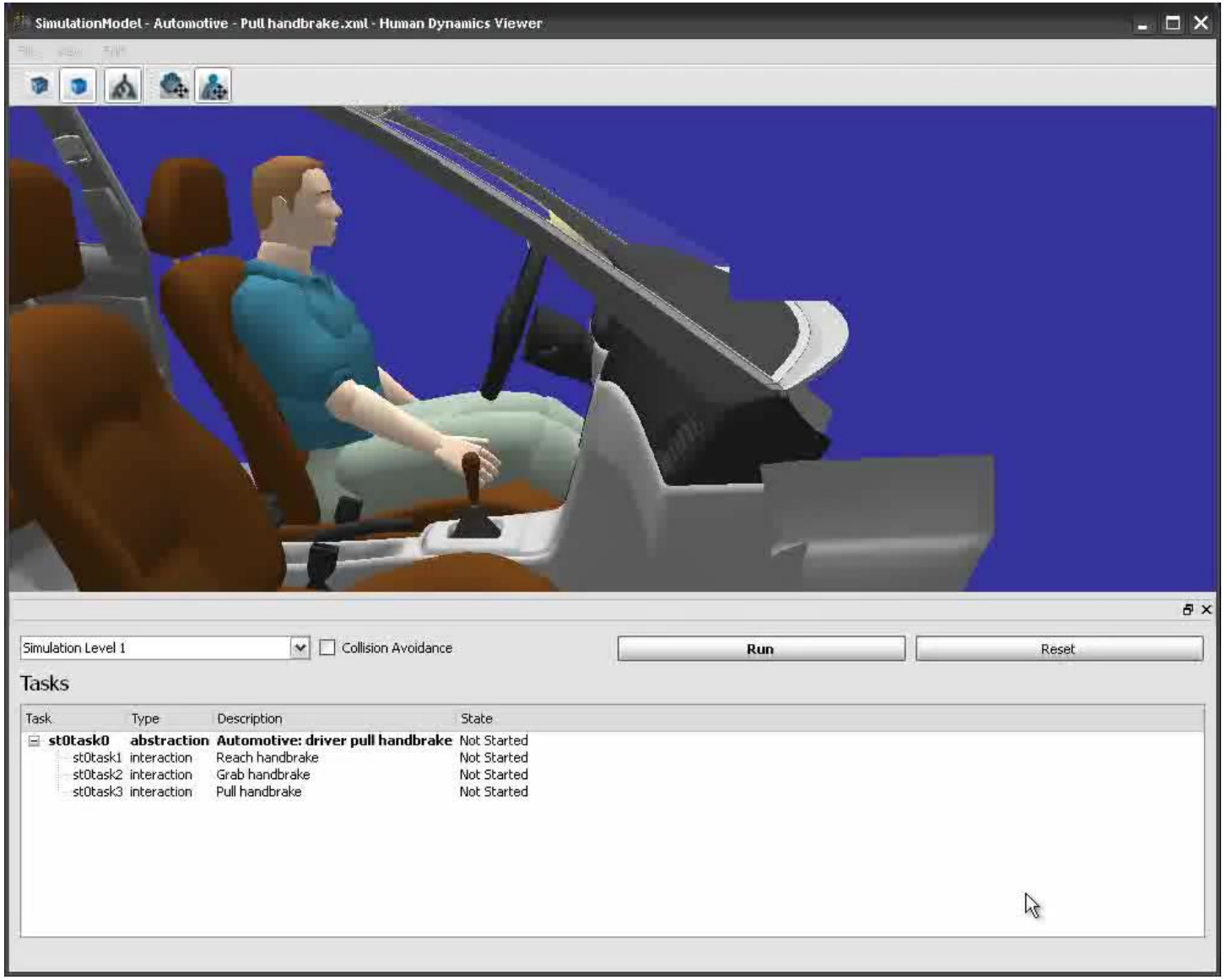


Example: Car interior-kinematics



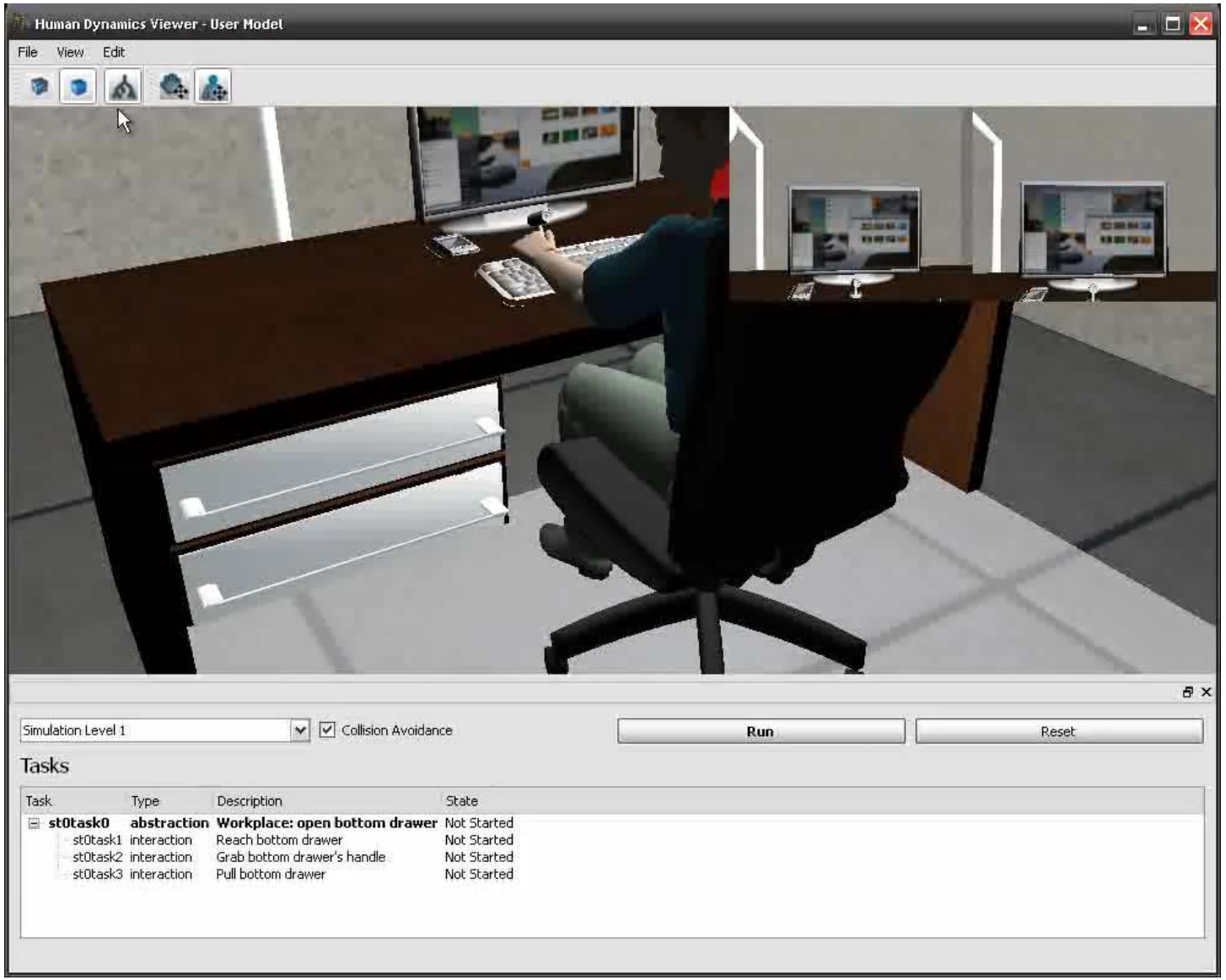
…in cooperation with CERTH/ITI

Example: Car interior-dynamics



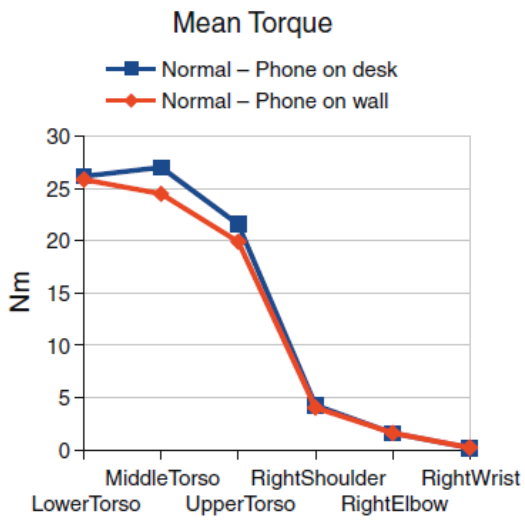
…in cooperation with CERTH/ITI

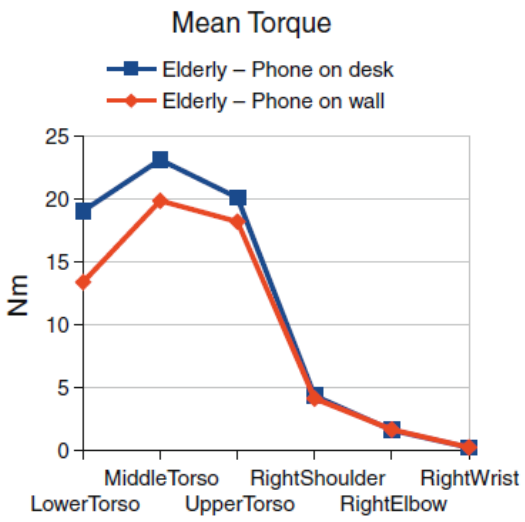
Example: Workplace-dynamics

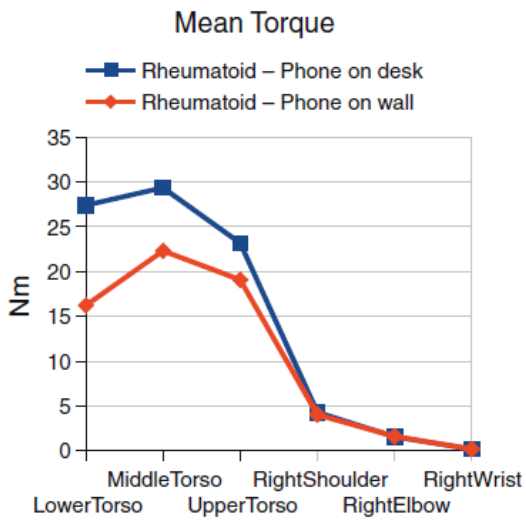


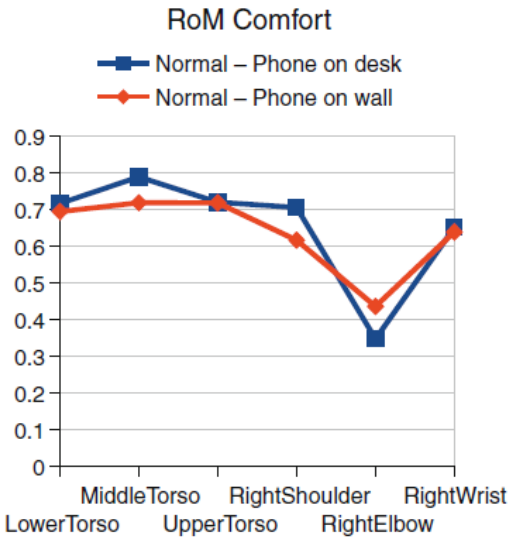
…in cooperation with CERTH/ITI

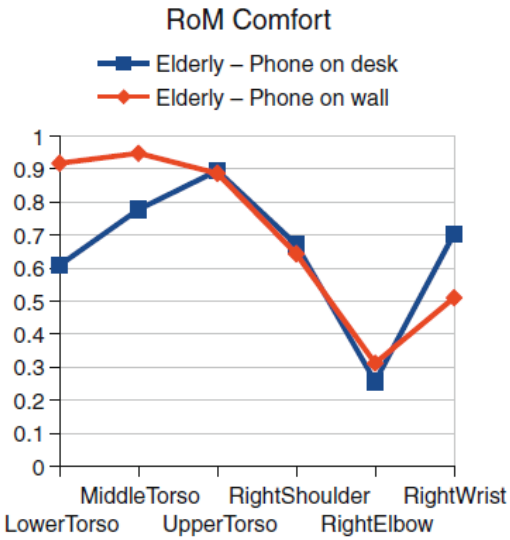
Output metrics example

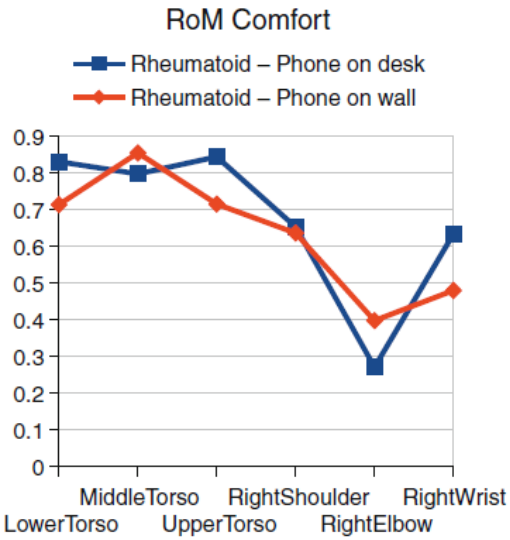








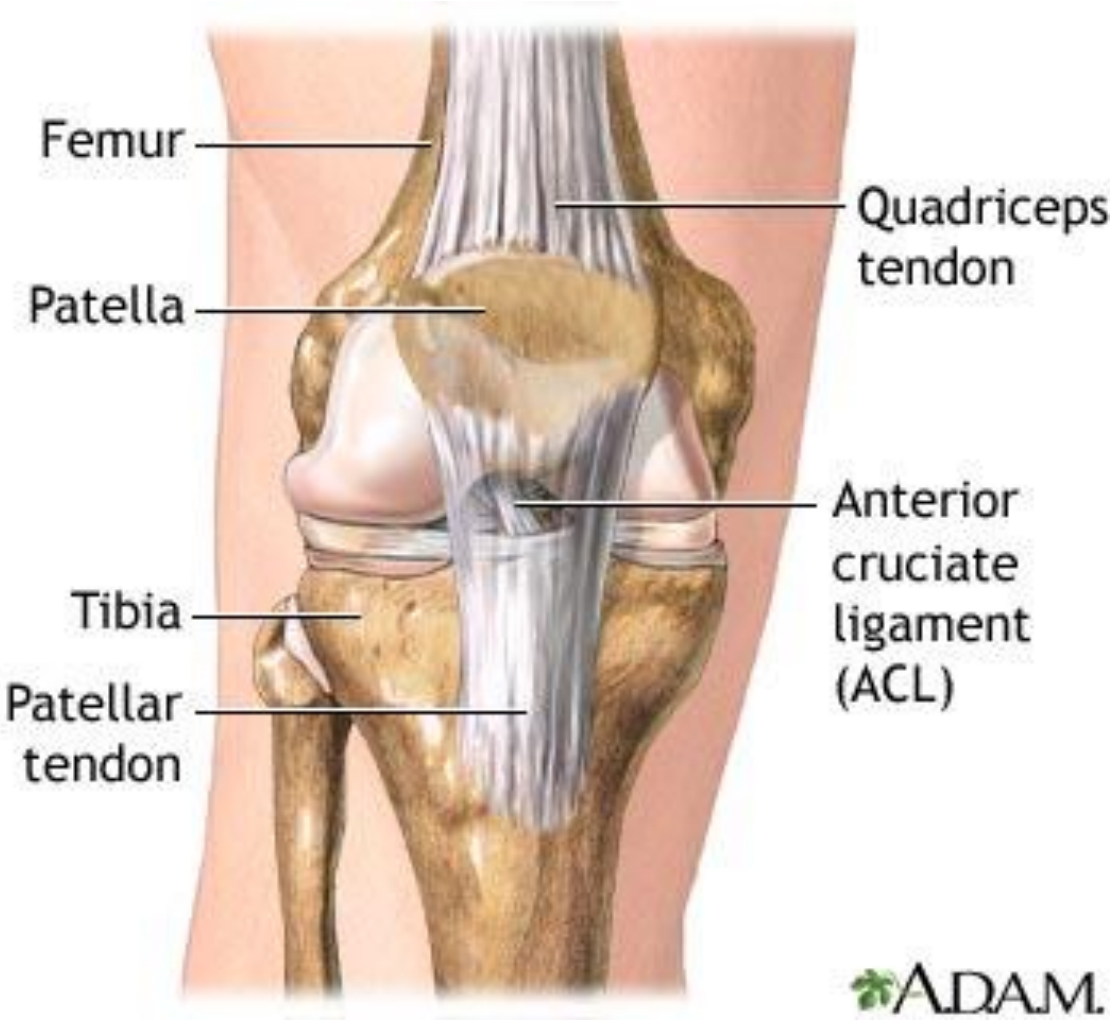




Virtual Physiological Human

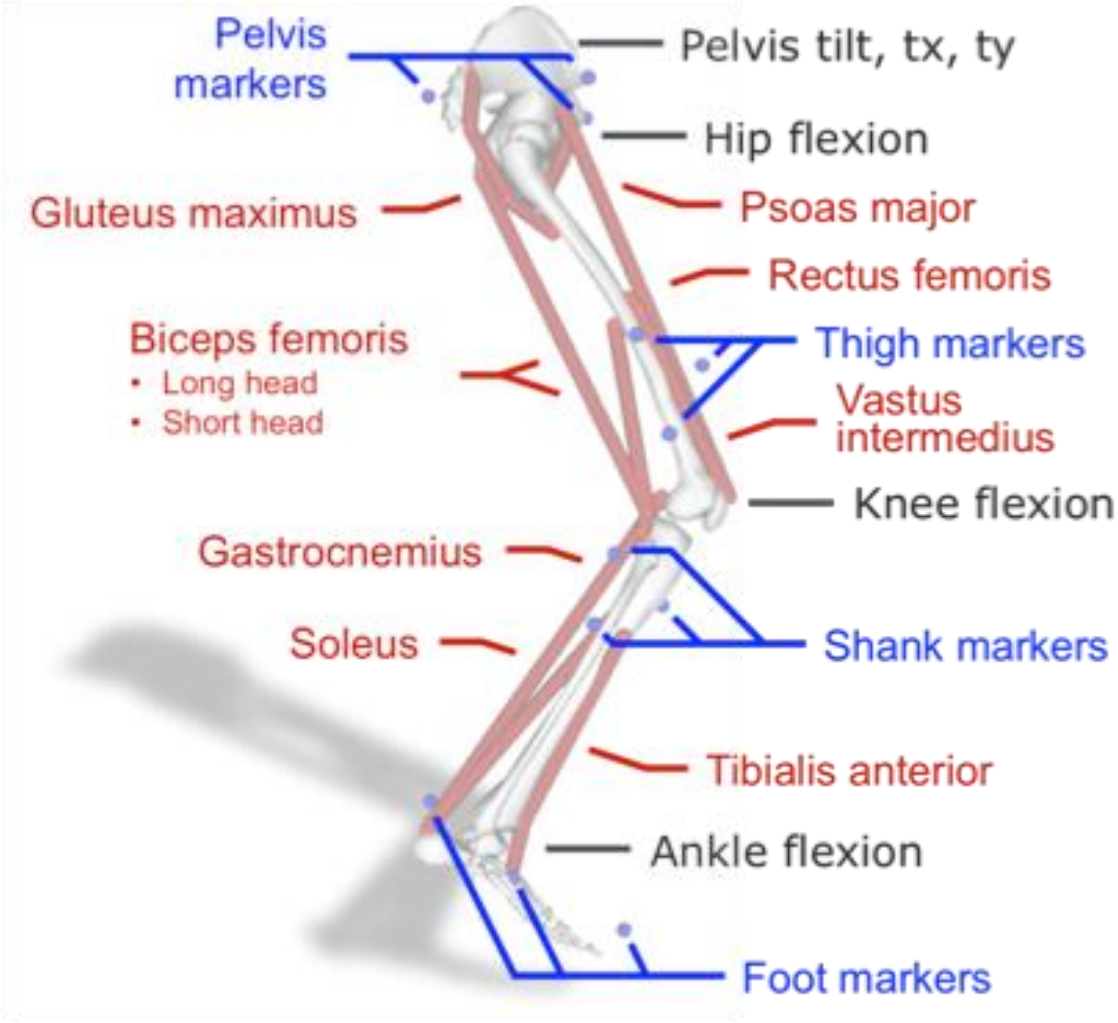
- *Motivation:*
  - *New research area, active for less that 10 years*
  - *Mathematically model parts of the human body*
  - *Augment factors like experience, clinical tests in medicine and drug discovery with quantitative models and simulations of behavior*
- *Simulation based solution*
  - *Test of new drugs in a simulated VPH environment in a virtual prototyping manner*
  - *Analysis of macroscopic results of medical treatment (quality of life)*
  - *Personalized treatment*
  - *Significant tools for research in medicine*

Example ACL tear



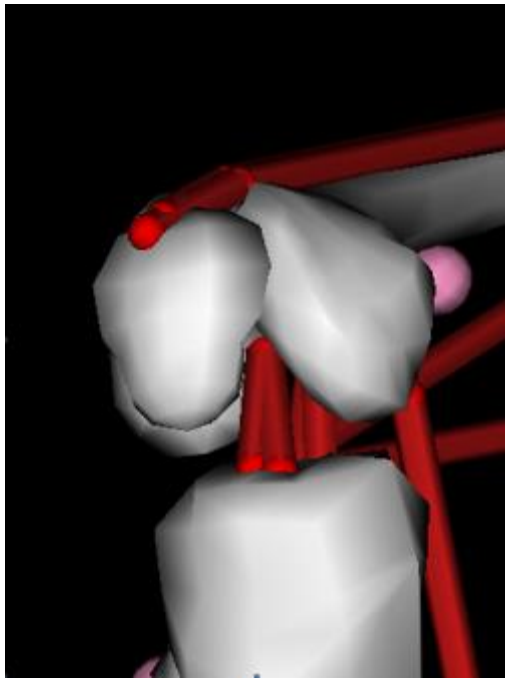
Example ACL-knee problems

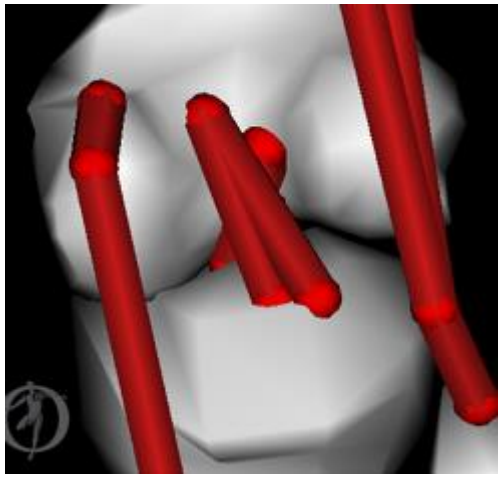
Modeling


Pelvis markers
Pelvis tilt, tx, ty
Hip flexion
Gluteus maximus
Psoas major
Rectus femoris
Biceps femoris
• Long head
• Short head
Thigh markers
Vastus intermedius
Knee flexion
Gastrocnemius
Soleus
Shank markers
Tibialis anterior
Ankle flexion
Foot markers

Modeling

- *Biomechanical knee model based on OpenSim*
  - Ligaments added to the model





Modeling

- *Biomechanical knee model based on OpenSim*
  - Ligaments added to the model
  - Parametric model so as to allow for customization:

Parameter type	Variable
ACL positioning	Tendon position coordinates
Dynamics parameters	Stifness, Damping, Tear
Model customization	Weight, Height
Actions	Activities to simulate
Muscle parameters	Activation dynamics

Modeling

e.g. physical vs synthetic transplant

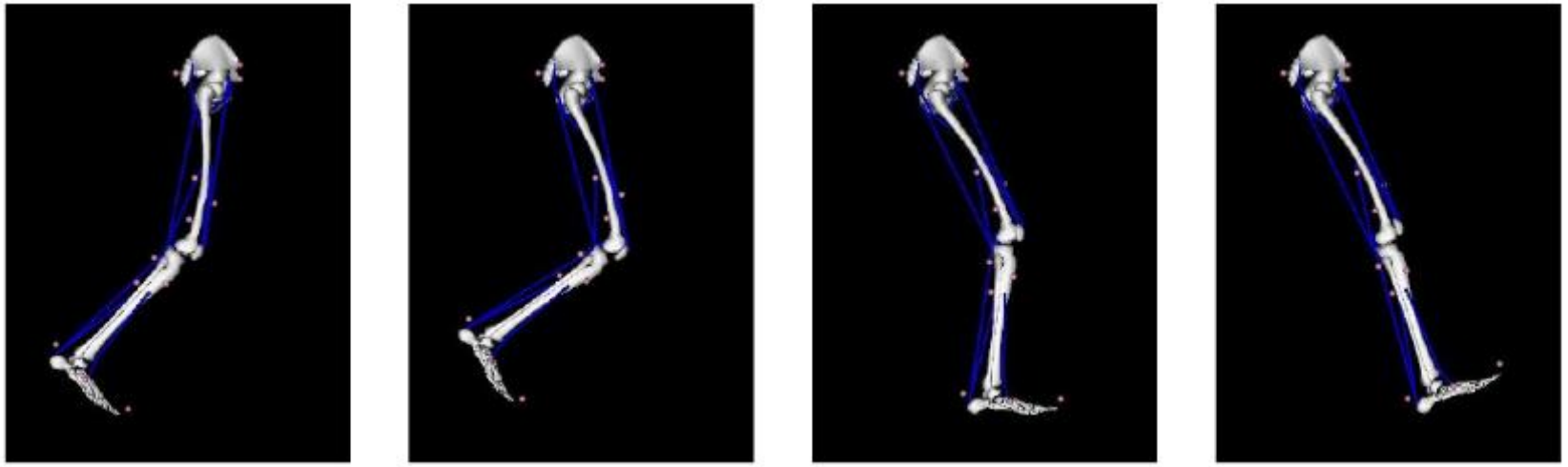
Surgical decisions

Parameter type	Variable
ACL positioning	Tendon position coordinates
Dynamics parameters	Stifness, Damping, Tear
Model customization	Weight, Height
Actions	Activities to simulate
Muscle parameters	Activation dynamics

Rough model customization

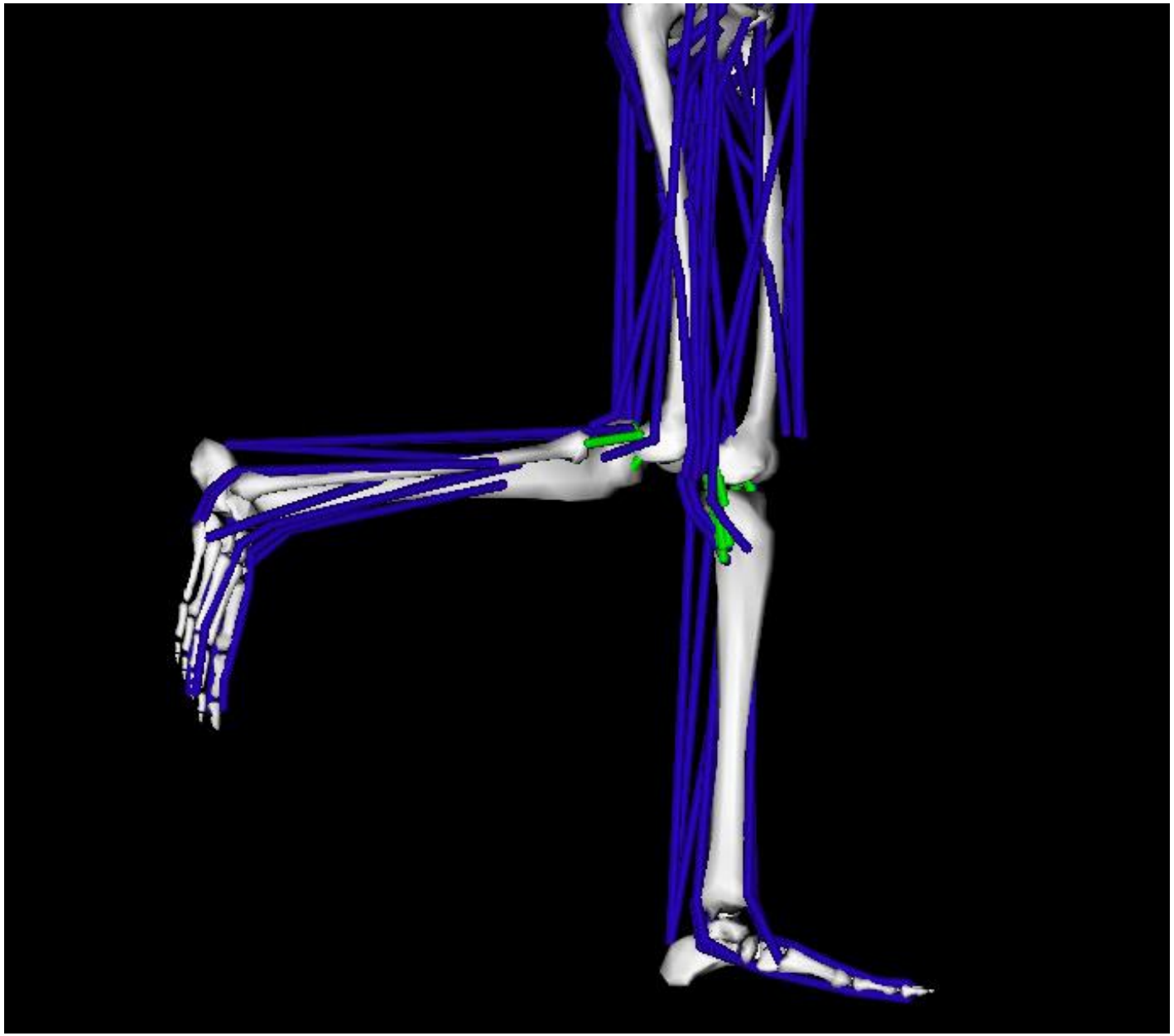
Potential activities to be simulated

Experiment

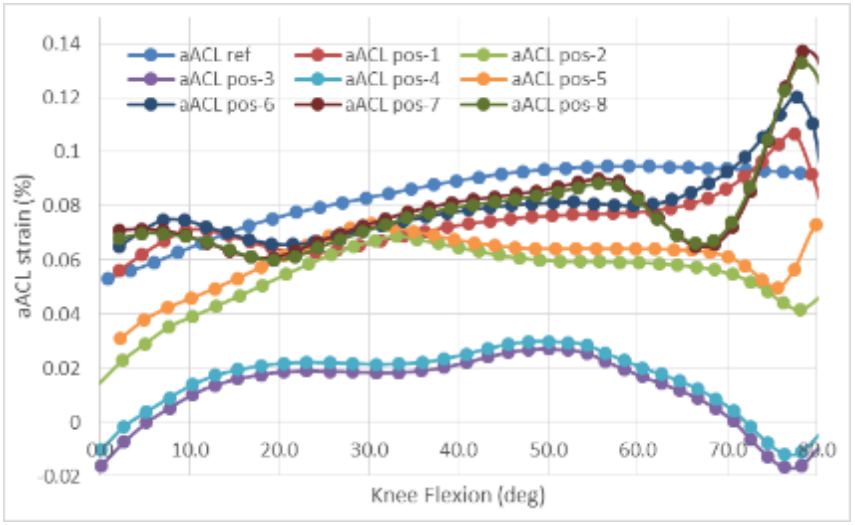


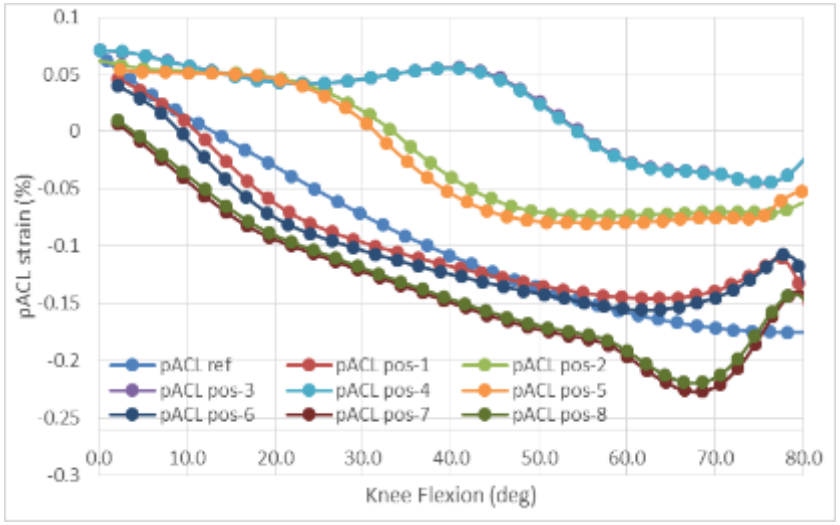
- *Swing action*
  - Half cycle swing action
  - No environmental response
  - Fixed at pelvis
- *Estimates*
  - Active muscle forces
  - Passive ligament forces

Swing action

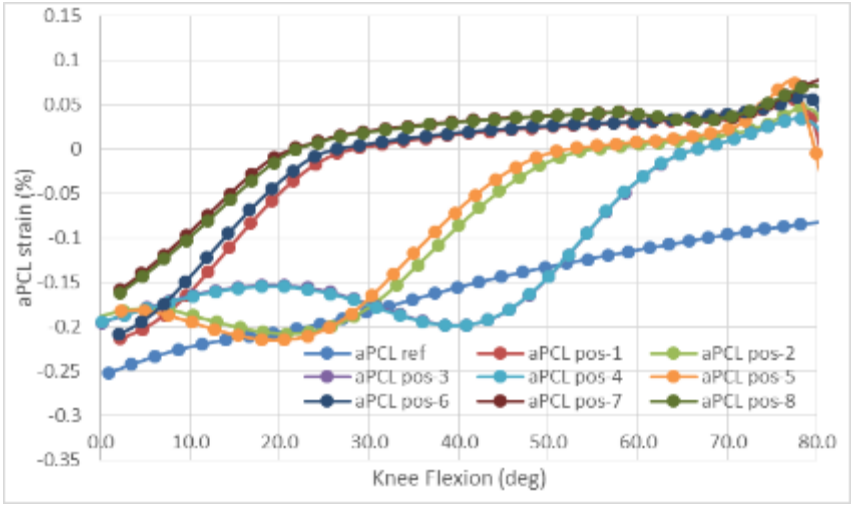


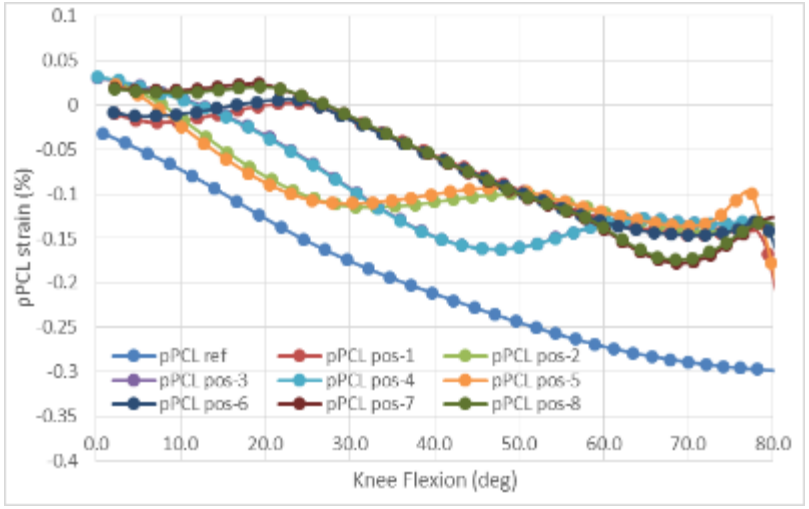
Results



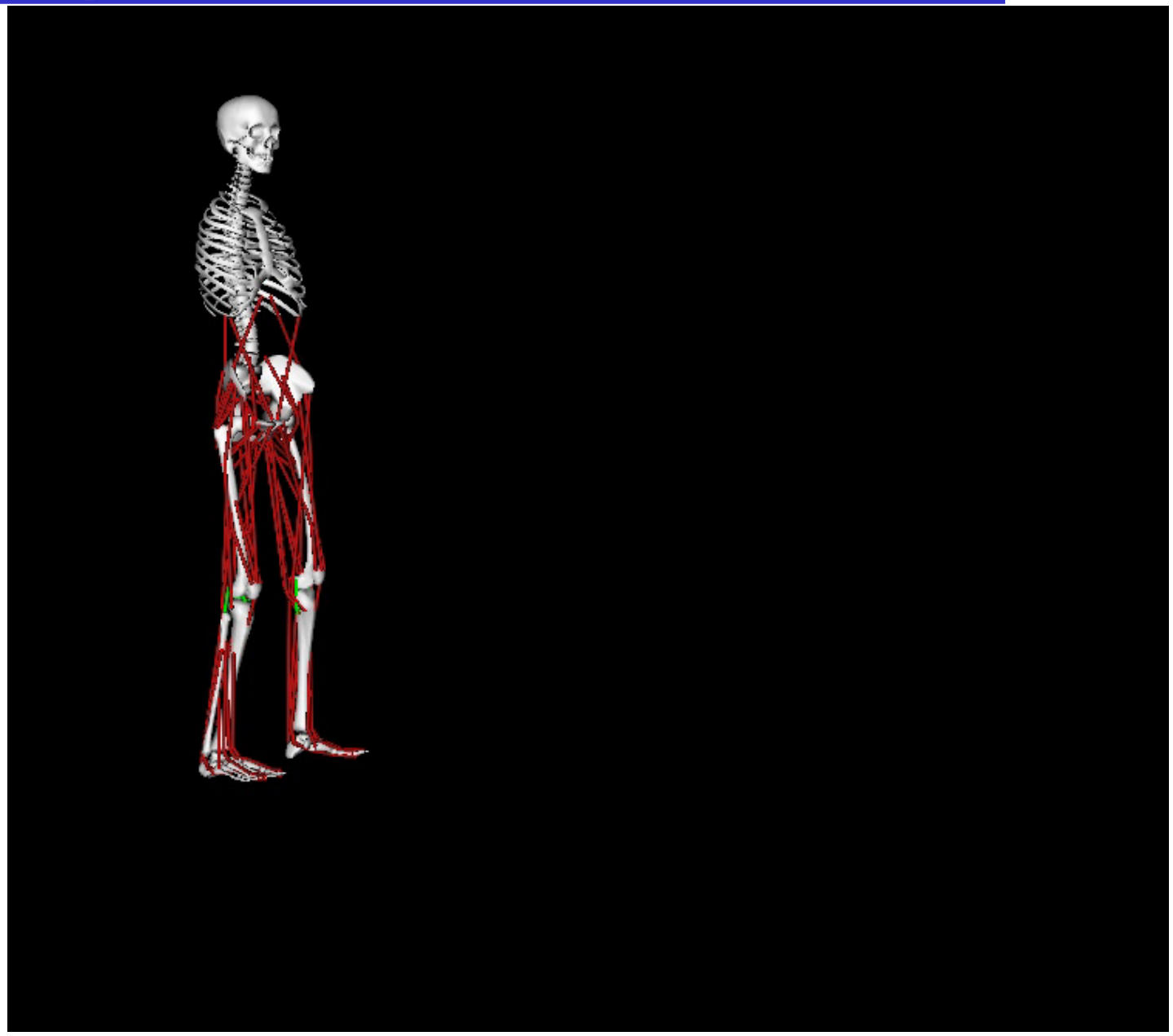


Surgical question: Positioning?

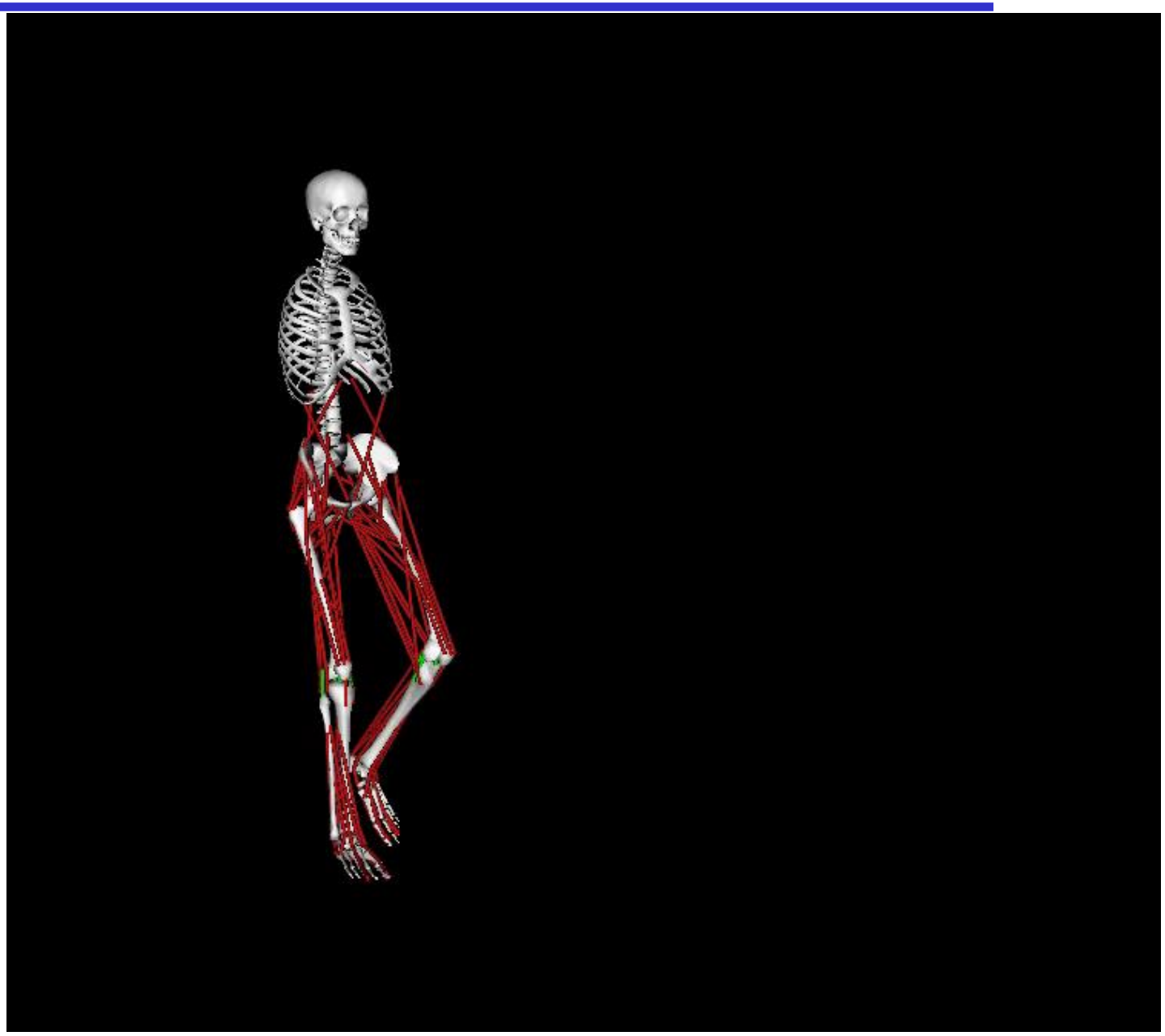




Jump

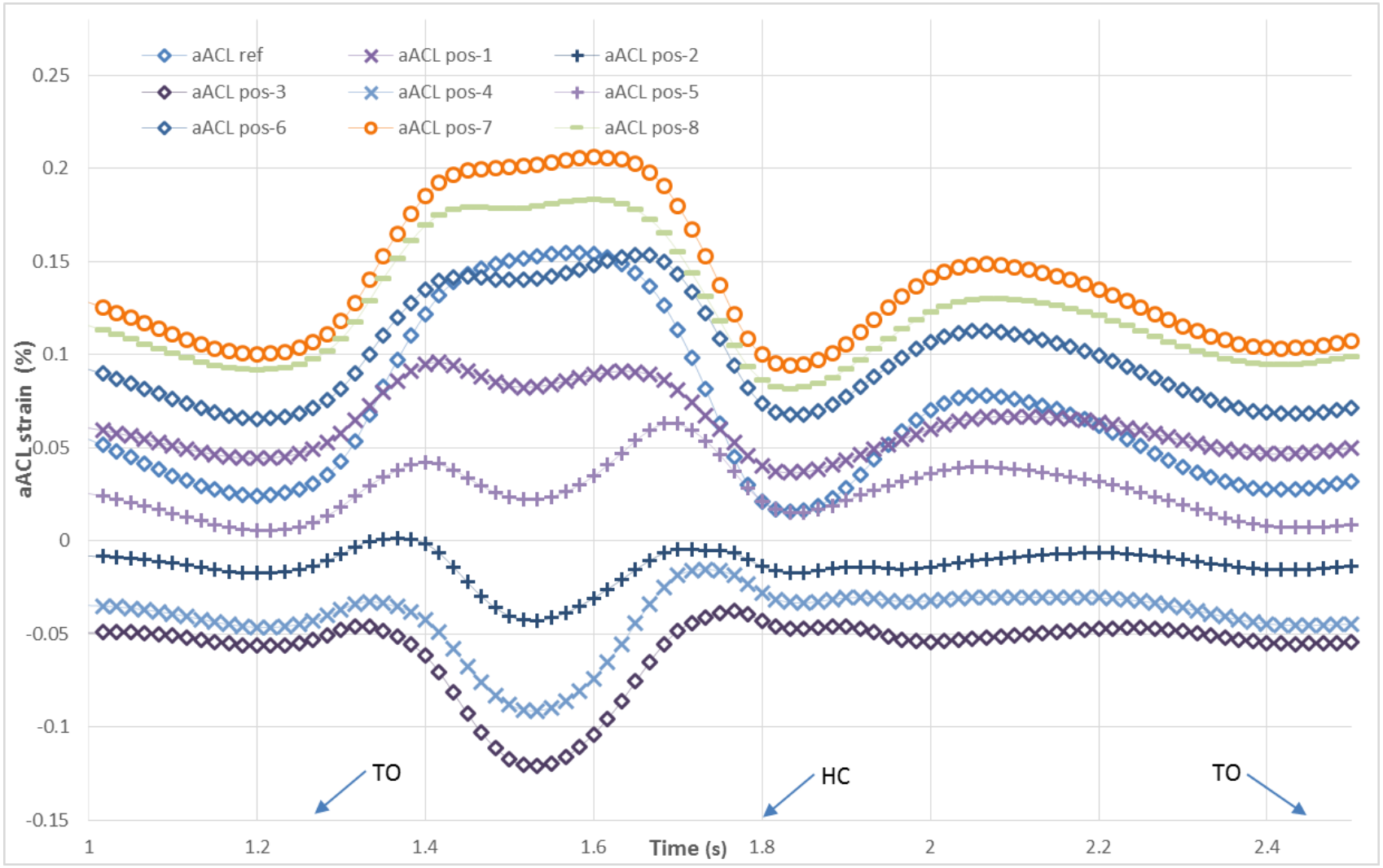


Gait



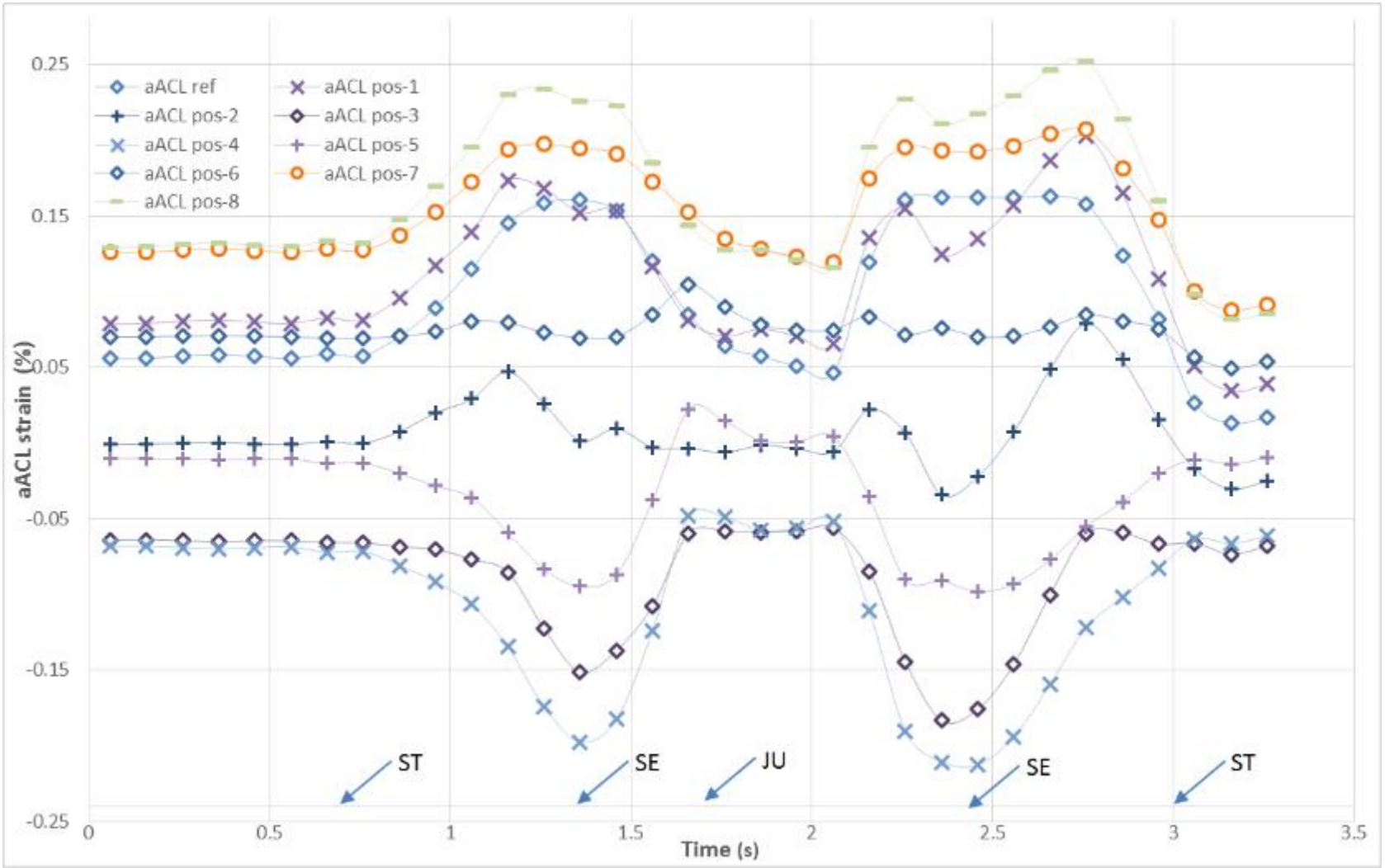
Results

Surgical question: Positioning!

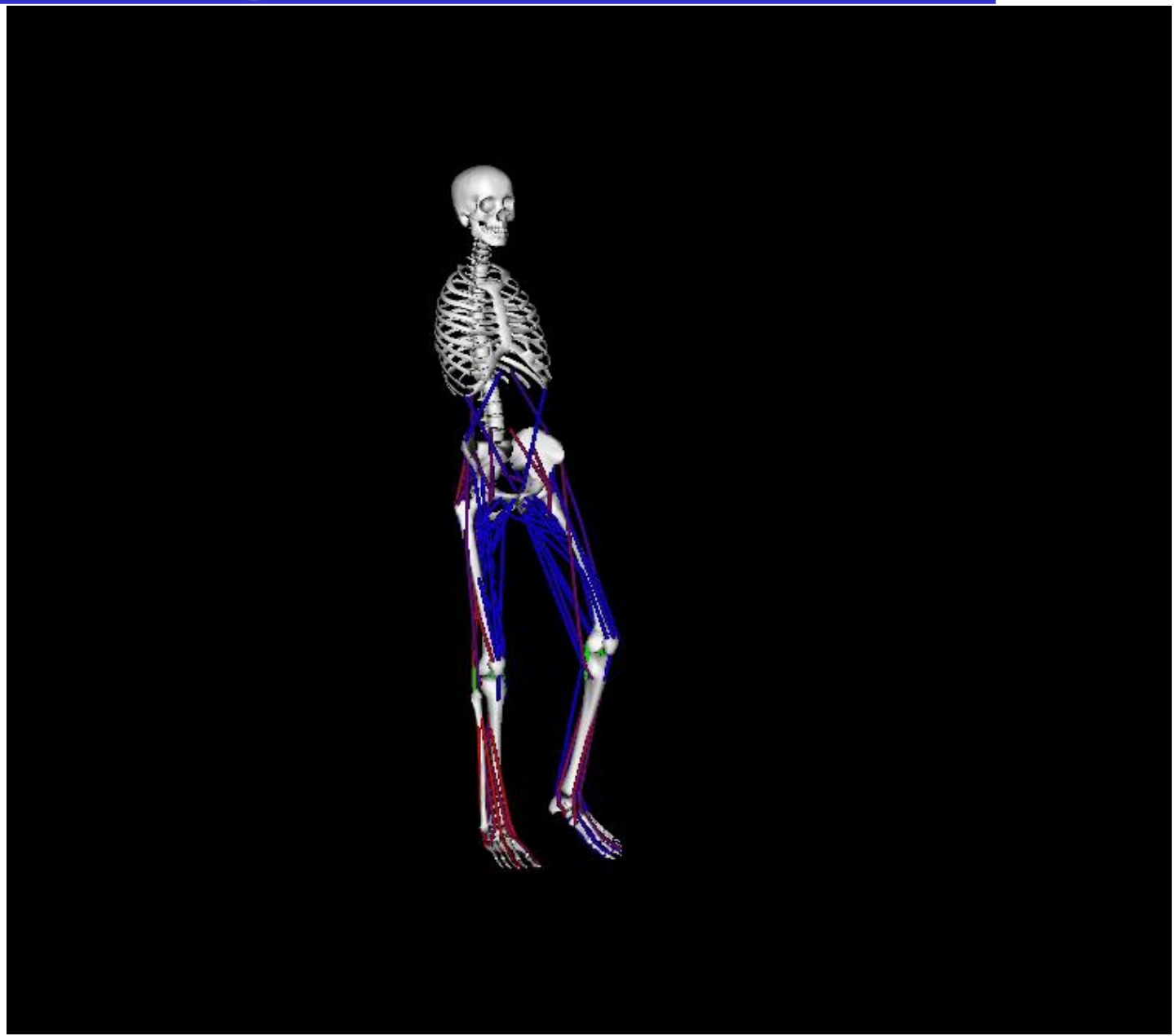


Results

Surgical question: Positioning!



Not always successful



Discussion – Future work

- Advantages:
  - VPH simulation of the knee with all the benefits this implies…
- Limitations – Future work:
  - Evaluation of the forces on the menisci (deformable objects!!)
  - Actions with environmental response