



ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Basic concepts of anatomy and mechanical modelling of the human body

Arturo Forner-Cordero

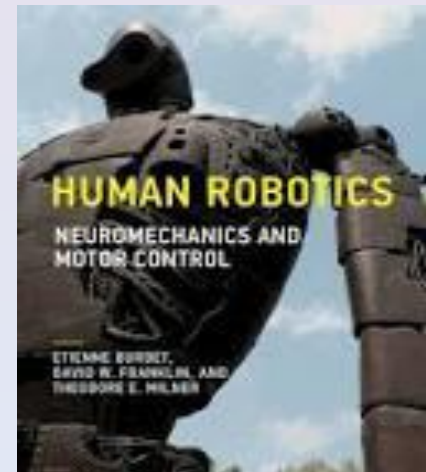
(aforner@usp.br)

Contents

Day	Topic
13/09/18	Introduction. Inaugural Lecture by Prof Duysens.
20/09/18	Basic concepts of anatomy and mechanical modelling of the human body
	Final project proposal (2 pages)
27/09/18	Robotics review: Kinematics and Dynamics
04/10/18	Sensors: Human body and BioRobotics
11/10/18	Biological actuators: Muscle
	Exercise list 1
18/10/18	Biological control architectures.
25/10/18	The CPG as cyclic motion control model
	Exercise list 2
01/11/18	Description and modelling of biological motor control
08/11/18	Project revision
15/11/18	Artificial compensation of neuromotor deficiencies Bioinspired robotic exoskeletons. Upper limbs.
22/11/18	Bioinspired robotic exoskeletons. Lower limbs. Bioinspired legged robots.
29/11/18	Presentations
	Final paper 06/12/2018
06/12/18	Presentations
24/01/19	Entrega final de trabalhos

Recommended books

- Biomechanics and Motor Control of Human Movement. DA. Winter.
- Introduction to Robotics, J.J. Craig. Pearson. 2005. 3rd Edition.
- Modelling and Control of Robot Manipulators. Sciavicco, L., B. Siciliano. Springer-Verlag. 2005.
- Neuromechanics of Human Movement. RA Enoka. 2006. 4th Ed.
- Robot Dynamics and Control. M.W. Spong, M. Vidyasagar. John Wiley & Sons, Ltd. 1989
- Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.
 - Chapter 3. Kinematics and dynamics of wearable robots. A. Forner–Cordero, J.L. Pons, E.A. Turowska.
- Human Robotics
Burdet E, Franklin DW and Milner T.E.
(MIT Press)





Bibliography (papers)

- An inverse dynamics model for the analysis, reconstruction and prediction of bipedal walking. B Koopman, HJ Grootenboer, HJ de Jongh - Journal of Biomechanics, 1995
- Forner Cordero, A.; Koopman H.F.J.M; van der Helm F.C.T. (2004) Use of pressure insoles to calculate the complete ground reaction forces. Journal of Biomechanics, 37(9): 1427-1432.
- Forner Cordero, A.; Koopman H.F.J.M; van der Helm F.C.T. (2003). Mechanical Model of the Recovery from Stumbling Biological Cybernetics. 91(4) 212-22. 2004.
- M.D. Klein Horsman, H.F.J.M. Koopman, F.C.T. van der Helm, L. Poliacu Proséb, H.E.J. Veeger. Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity. Clinical Biomechanics. Volume 22, Issue 2, 2007, Pages 239–247
- **Multibody Dynamics B. R.Q. van der Linde and A. L. Schwab**
<http://bicycle.tudelft.nl/schwab/wb1413spring2012/MultibodyDynamicsB.pdf>



Evaluation

- Final Project: (in English)
 - Paper for Journal or Conference: min. 6 pages (IEEE Conferences format)
 - Develop and build a device and provide the documentation
- Presentations of the work (15 min, conference format).
- Literature and patent review:
 - Bibliographic review: Methodology
 - Critical paper review
- Final presentation (15 min, conference format).

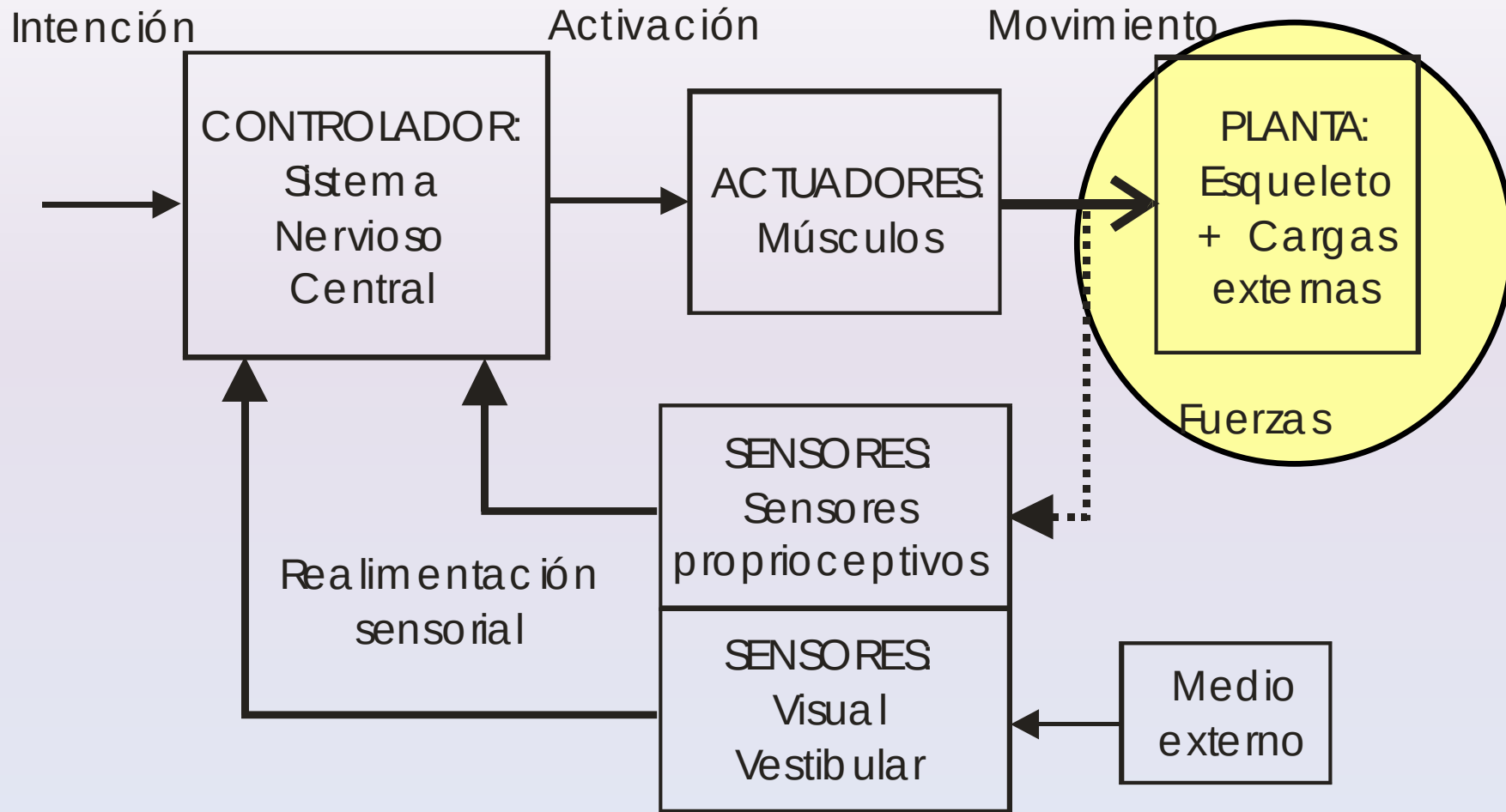


Bibliografía

- Chapter 3. Kinematics and dynamics of wearable robots. A. Forner–Cordero, J.L. Pons, E.A. Turowska. In: Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.
- Modelling and Control of Robot Manipulators. Sciavicco, L., B. Siciliano. Springer-Verlag. 2005.
- Forner–Cordero A, Koopman HFJM and van der Helm FCT 2004 Use of pressure insoles to calculate the complete ground reaction forces. *Journal of Biomechanics* 37(9), 1427–32.
- Forner–Cordero A, Koopman HFJM and van der Helm FCT 2006 Inverse dynamics calculations during gait with restricted ground reaction forces information from pressure insoles. *Gait & Posture* 23 (2), 189–199.

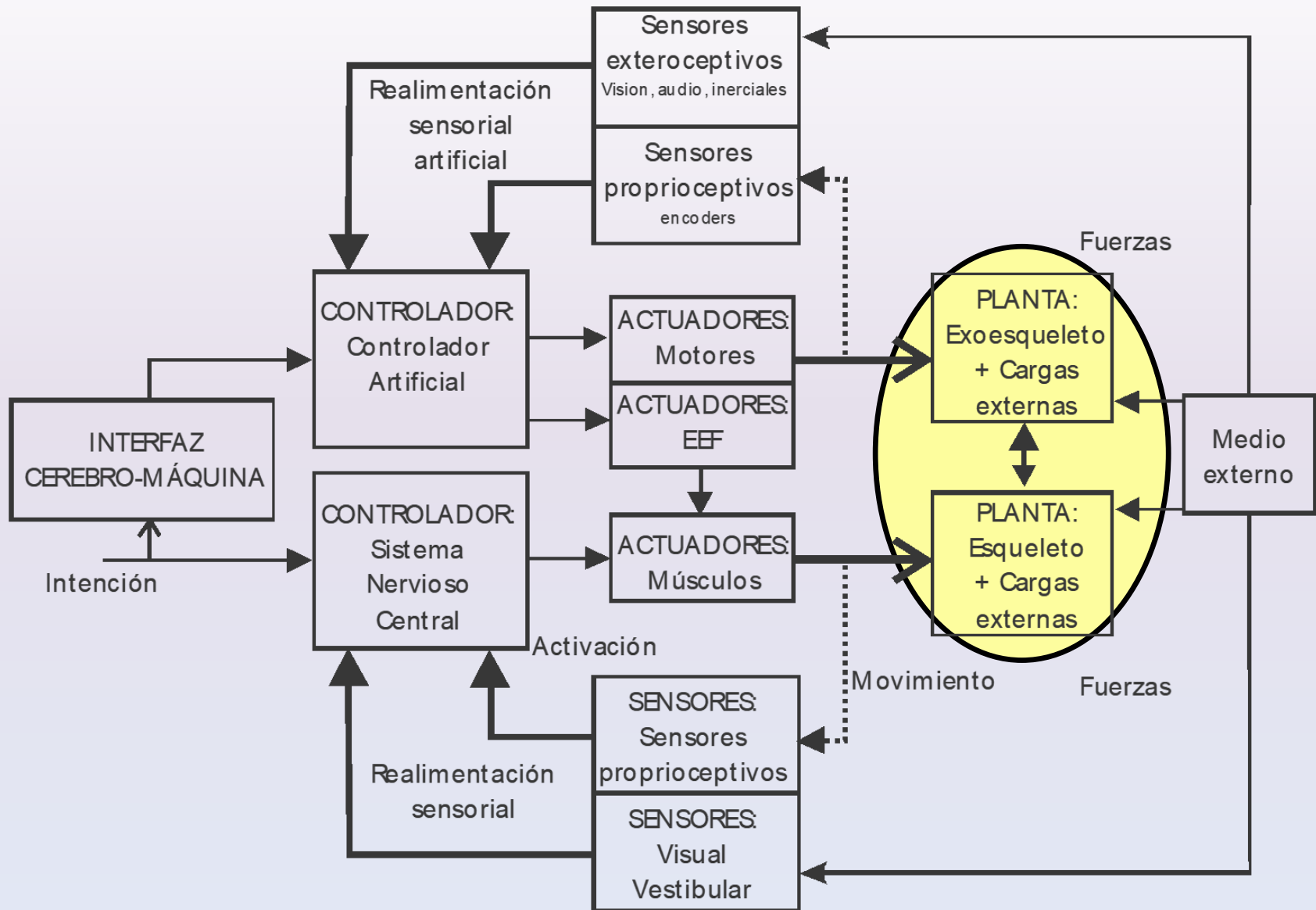


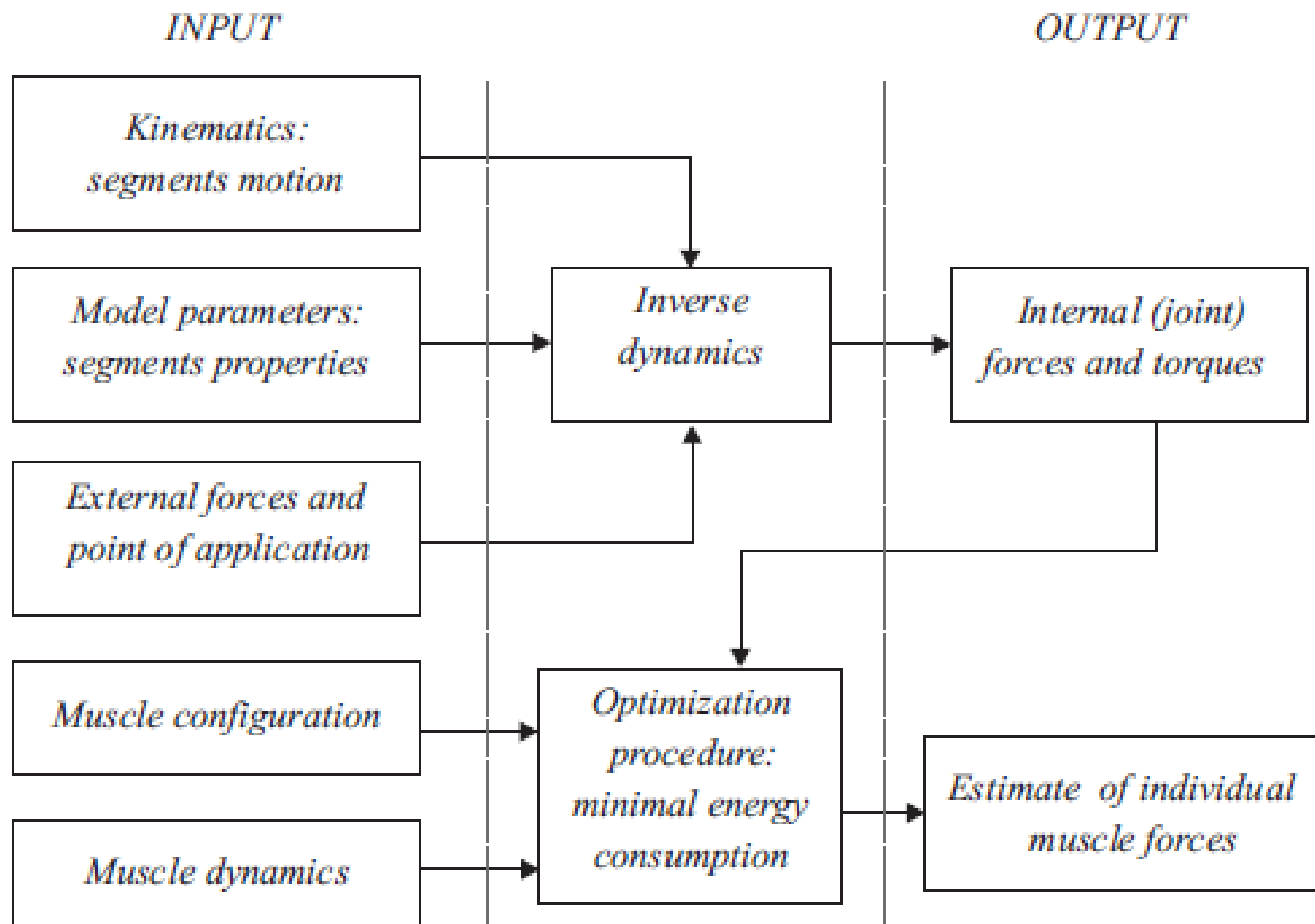
Human motor system





Human-robot motor system





Tema 2

1. Modelling of the human movement
 - Rigid body dynamics
2. Description of human movement:
 - Medical
 - Technical
3. Measurement of human movement
4. Rigid body motion description
5. Inverse (and direct) Dynamics
6. Application: Inverse dynamics analysis



1. Modelling of the human movement

1.1. Motor system structures

1.2. Assumptions

1.3. Rigid body dynamics

Segment model



Motor system structures

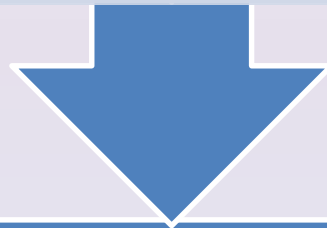
Anatomical structure

High stiffness tissues

Bones: skeleton

Low stiffness tissues

Organs, muscles



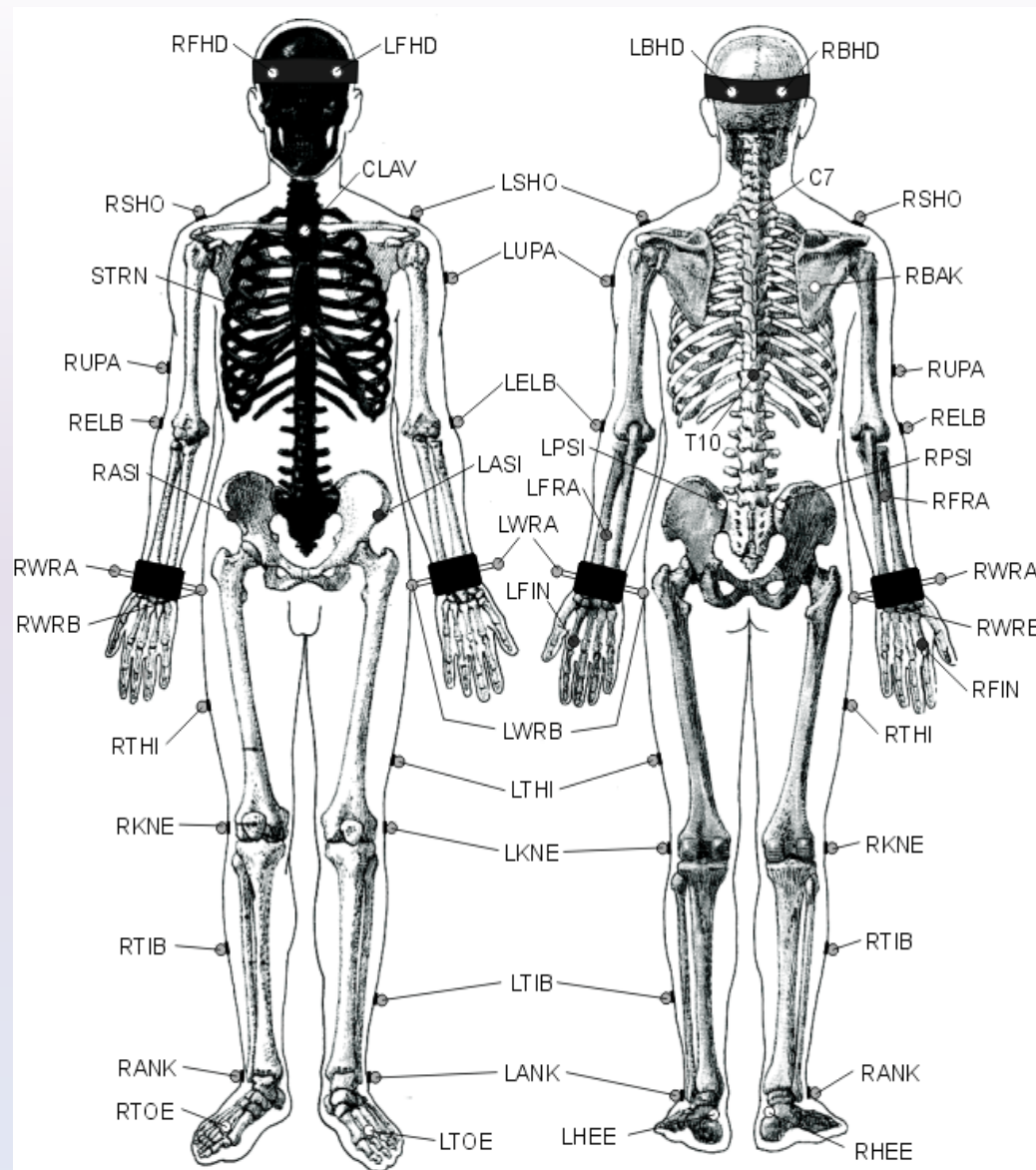
Mechanical system

Segments

Joints

Actuators





VICON. (OMG)
Plug-In-Gait



Assumptions

- Biomechanical modelling:
 - Assumptions:
 - Rigid bodies: bones
 - Deformations occur only at the joints
 - System of rigid bodies
 - Tissue deformations:
 - Finite Element analysis
 - Inverse dynamics analysis



Rigid body dynamics

- Movement description: kinematics
- Forces description: dynamics
- Link or segments model
 - How to define it?
 - What information is needed?
 - N^o of segments
 - Segment dimensions
 - Inertial parameters
 - Degrees of freedom of each joint



Segment model

- Rigid bodies
 - Measured properties of the human body:
 - Lengths, CoM positions
 - Inertial properties
 - N^o of segments
 - Degrees of freedom (DoF)
- Kinematic description
 - Markers
- Dynamics



Biomechanical models

- Segments and joints models
 - Human body joints
 - Joint types
 - Segments
 - Segment types
 - Model errors
- Motion measurements
 - Measurement errors

2. Human movement description

2.1. Medical description:

- Joints
- Movement planes
- Movement description

2.2. Technical description:

- Rotation matrix+translation vector
- Euler angles, helical axis, quaterniones
- Denavit-Hartenberg



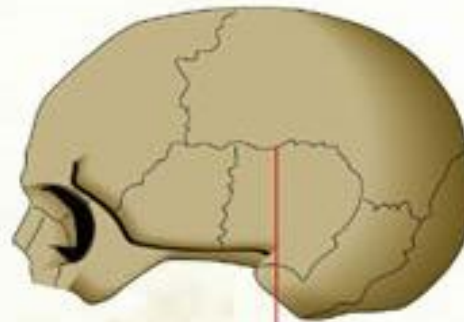
Joint types



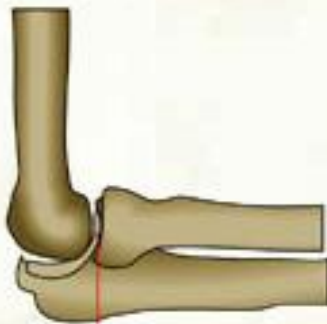
ribs and vertebrae =
semi-mobile joints



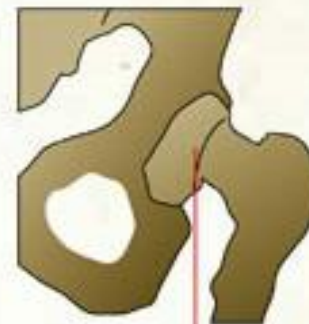
vertebrae =
cartilagenous joints



skull=
immovable joints



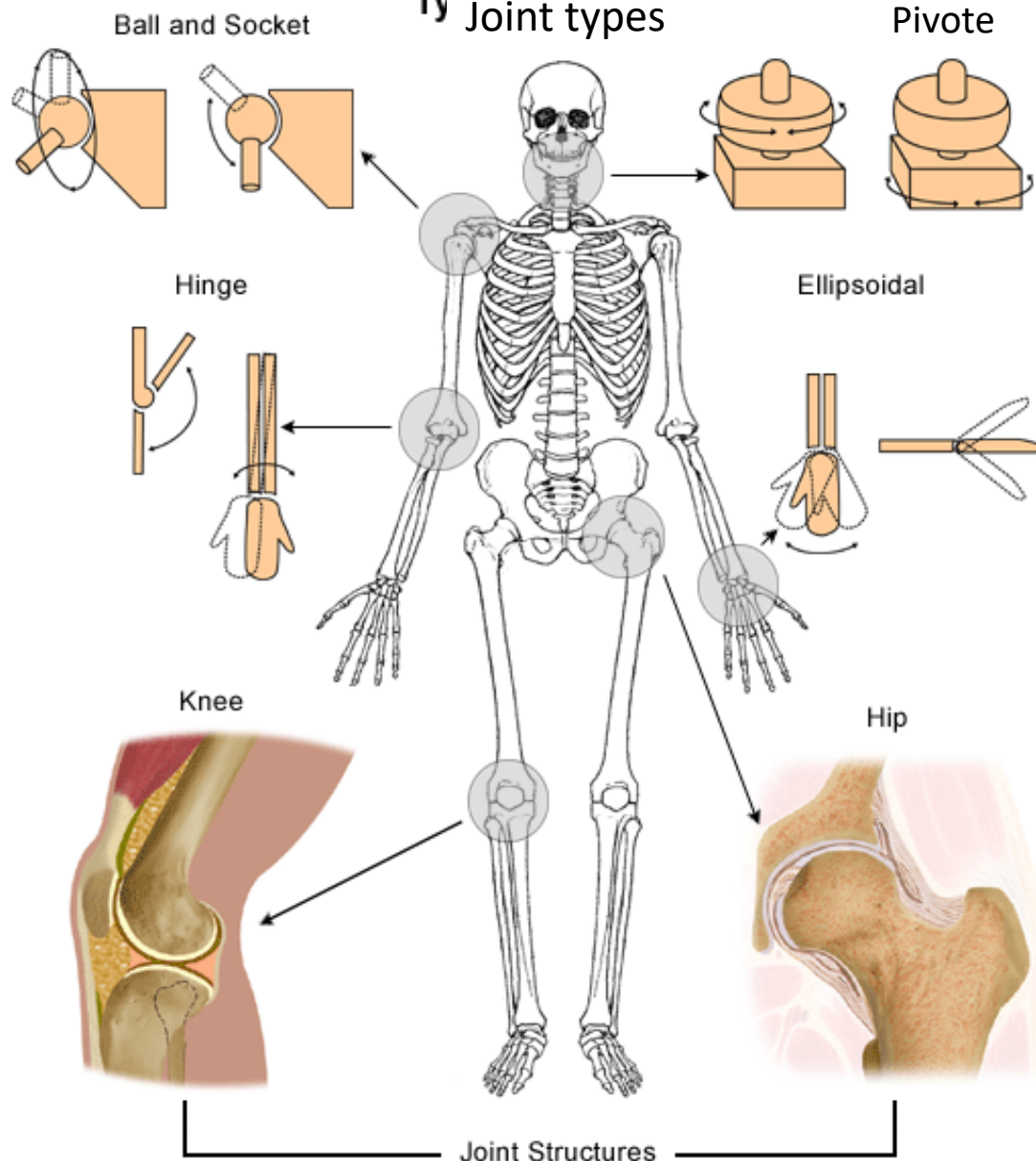
elbow=
hinged joint



hip=
ball and socket joint



Joint types



Dobradiça

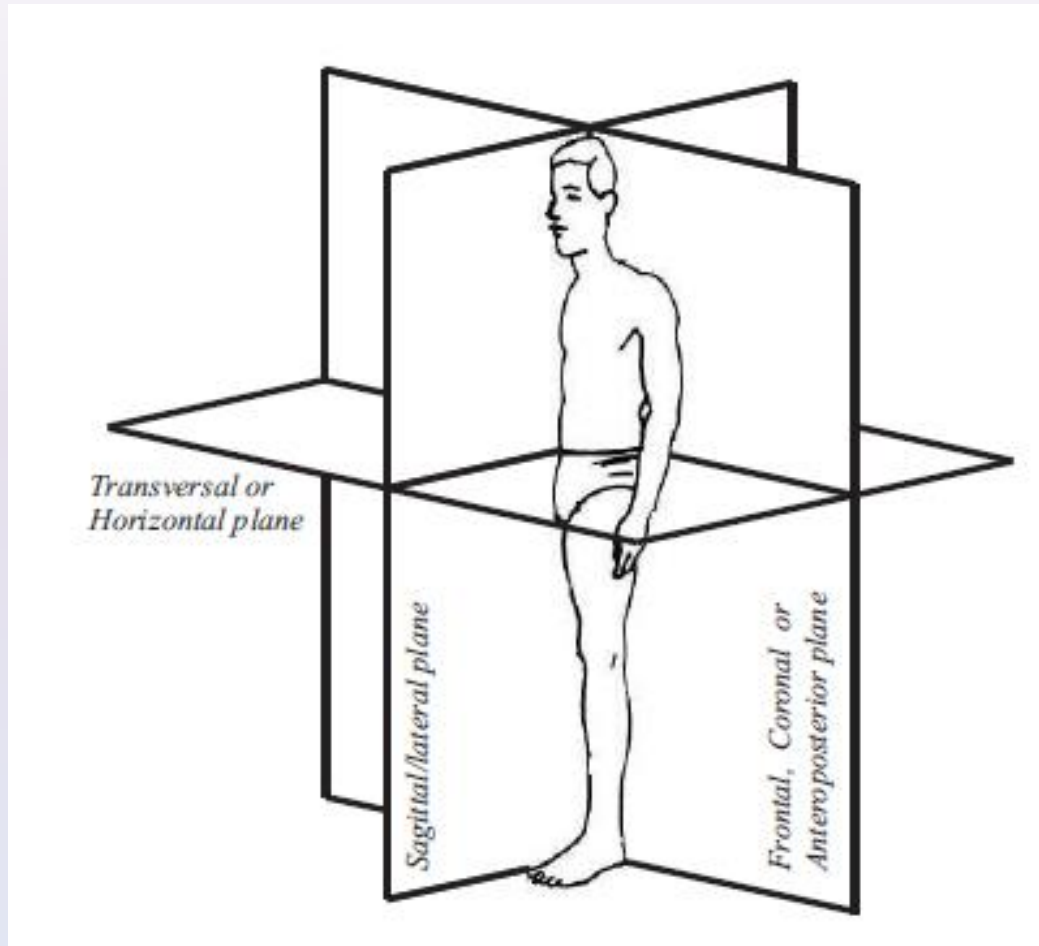
Joelho

Elipsoidal

Quadril



Anatomical planes



Chapter 3. Kinematics and dynamics of wearable robots. A. Forner-Cordero et al. In: Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.

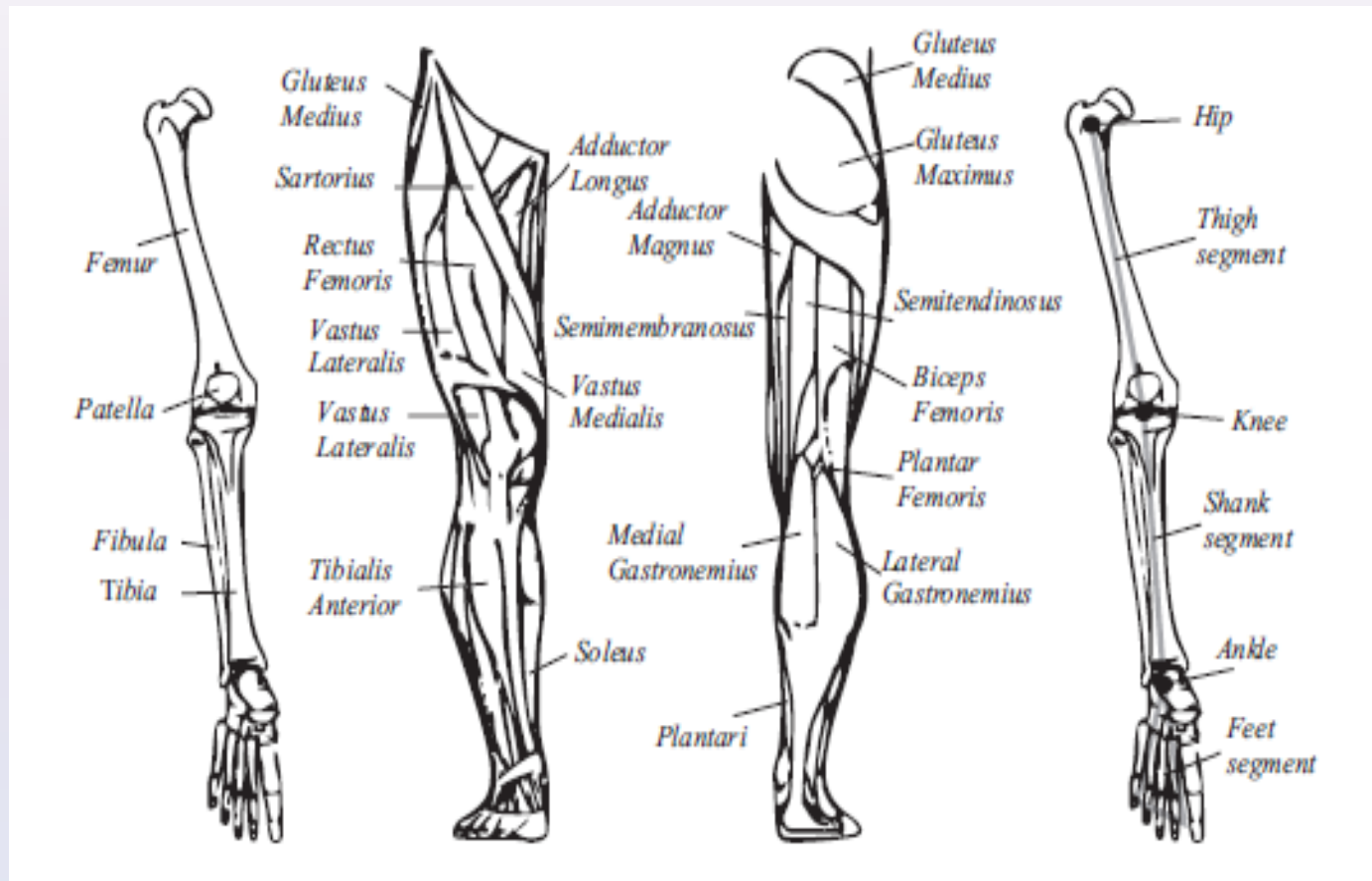


Planos anatómicos

- *Frontal or coronal plane:*
 - *Divides the body in anterior and posterior sides*
- *Transversal plane:*
 - *Divides the body in superior and inferior parts*
- *Sagittal or lateral plane*
 - *Divides the body in right and left sides*

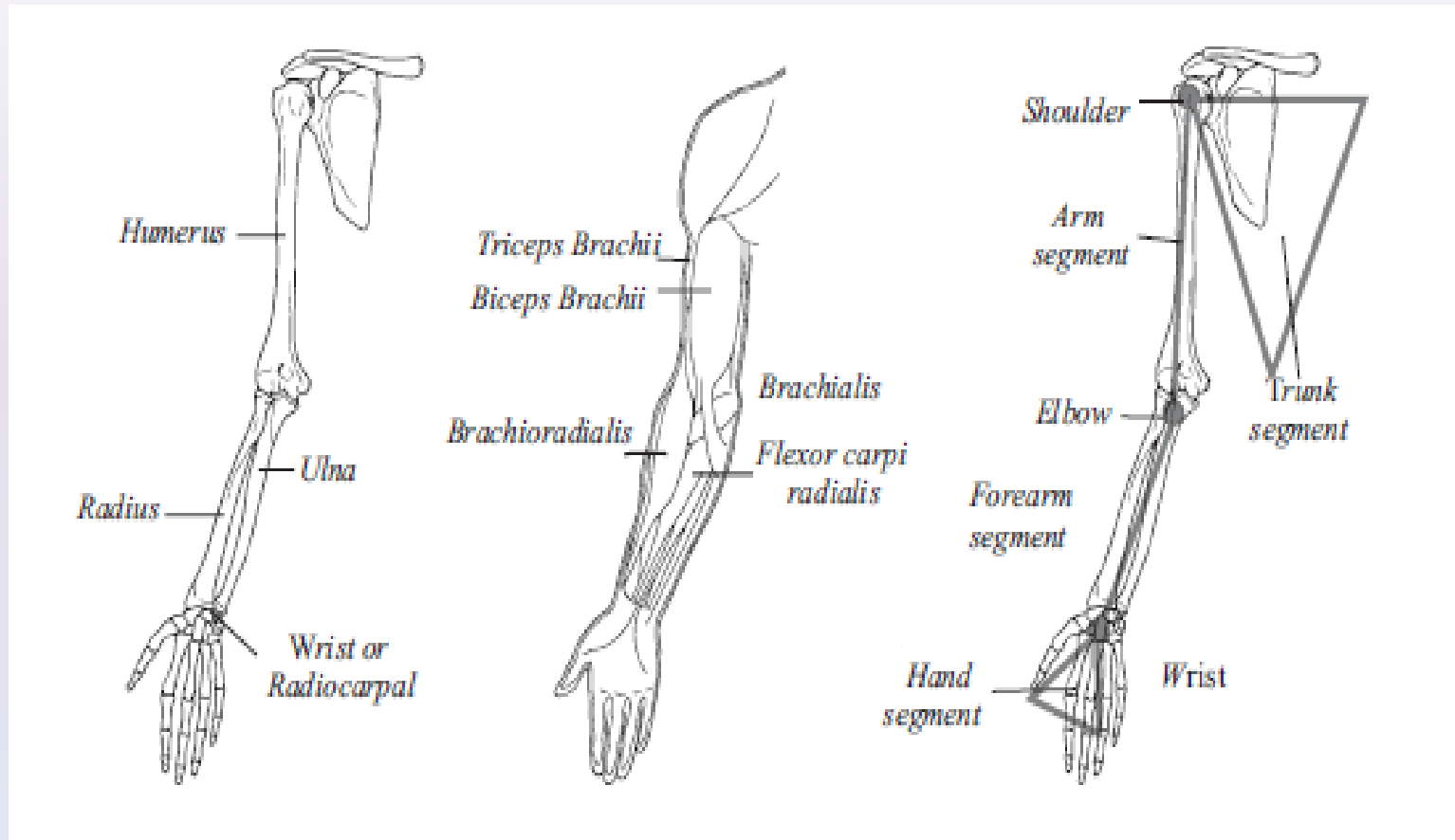


Leg anatomy





Arm anatomy and segments model



Medical description of movement

- Sagittal plane movements: Flexion-Extension
 - *Flexion: reduction of the angle between bones or body segments*
 - *Motion restriction to a plane*
 - *Ankle flexion would be dorsiflexion*
 - *Extension: increase the angle between bones or body segments*
- *Ankle extension would be plantarflexion..., but*

Medical description of movement

- Coronal plane movement:

abduction-adduction:

- ***Abduction*** limb motion away from the medial plane of the body; (*ab* -> *away*)
- ***Adduction*** limb motion towards the medial plane of the body;
 - Oposite of *abduction*.

Medical description of movement

- *Supination-pronation:*
 - Supination: Rotation of the arm to let the palm of the hand upwards.
 - Pronation: Rotation of the arm to let the palm of the hand downwards.
- *Rotation, internal or external*, circular joint motion around the long axis of the bone.
- *Circumduction*, circular movement combining a sequence of flexion, abduction, extension and adduction (e.g. shoulder or hip).

Medical description of movement

- Pathology description and assessment
- Ambiguity:
 - Movement around several axes
 - Combinations of rotations and translations
 - No clear rules to define the order of rotations
 - The planes and axis rotate with the movement?
 - Elbow flexion with the shoulder in abduction...
- **CONCLUSION:** This movement description is **CONFUSING** (at least for Engineers)



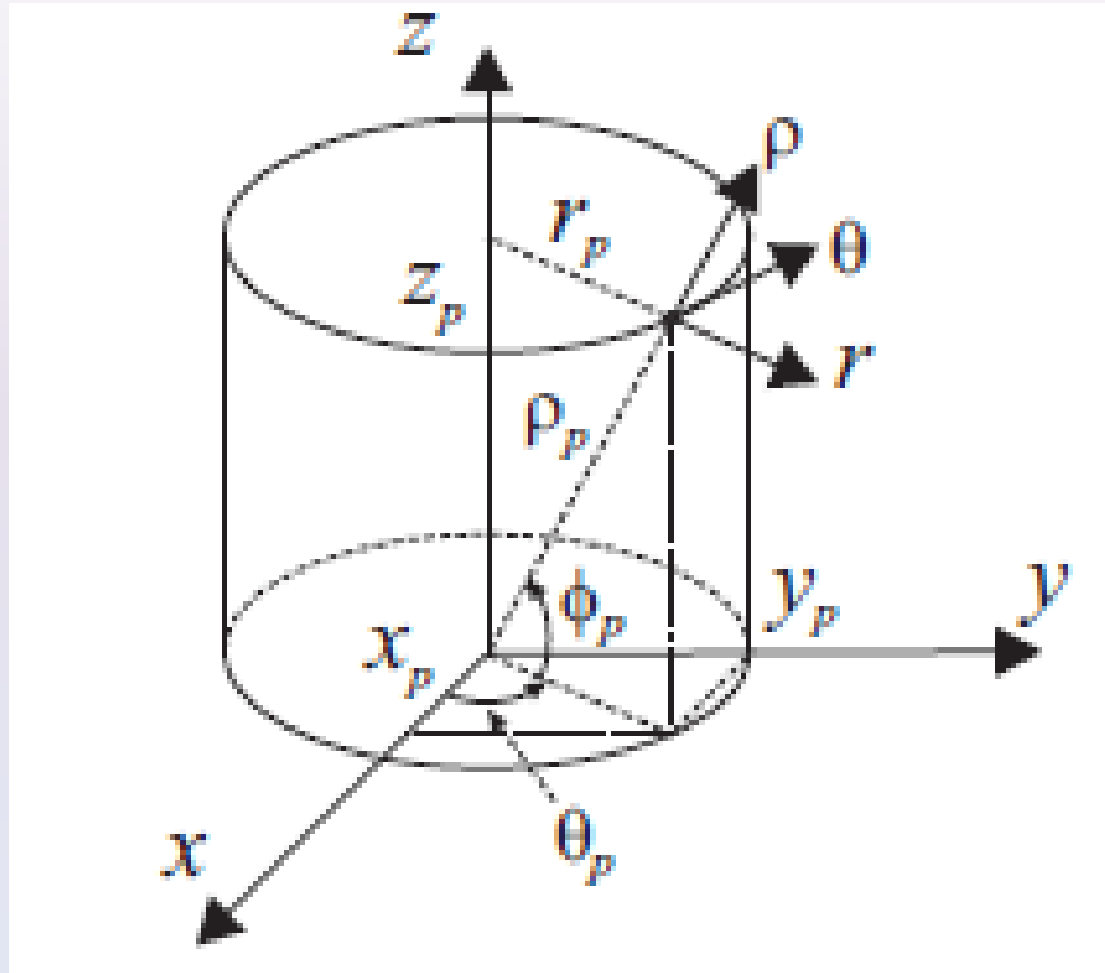
Technical description of movement.

Kinematics

- Methods to describe rigid body kinematics
- Heuristic methods
- Denavit-Hartenberg
- Rotation description:
 - Medical description
 - Technical description:
 - Euler
 - Helical Axis
 - Quaternions



Technical description of movement





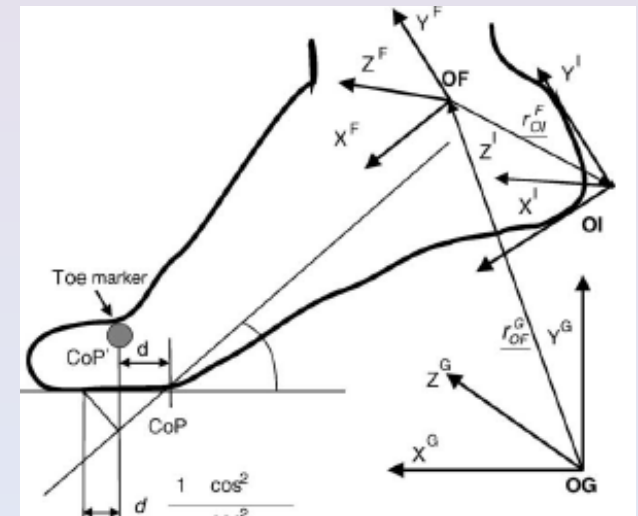
Rotation matrix and position vector

$$\vec{r} = \vec{p} + \mathbf{R}\vec{s}$$

$$\mathbf{R} = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix}$$

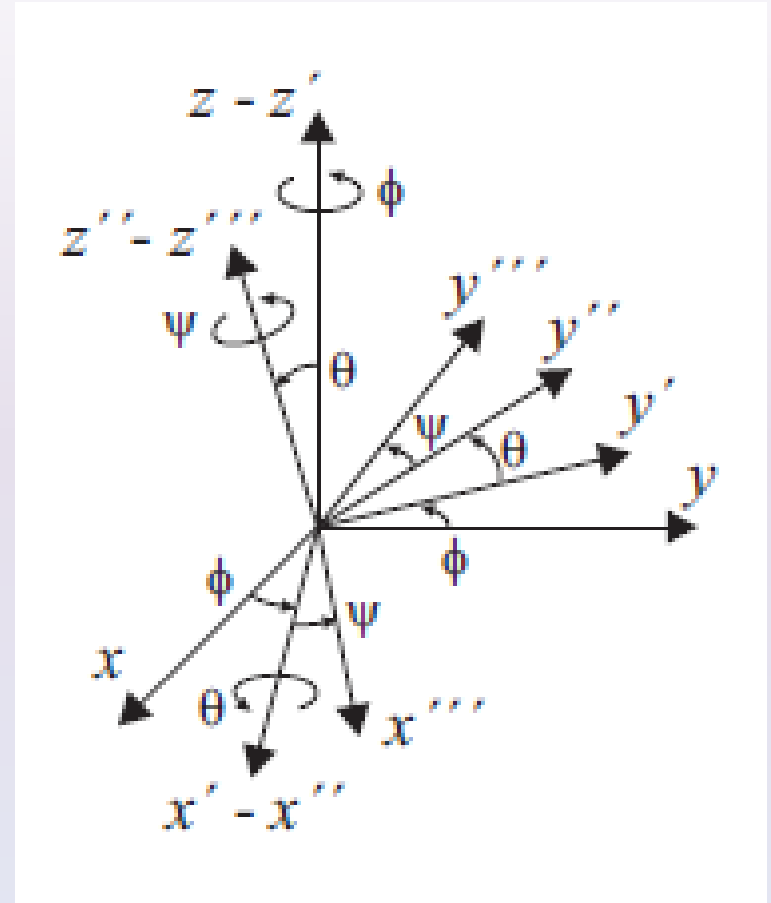
$$\mathbf{R}^{-1} = \mathbf{R}^T$$

- $\vec{p}$ origin position vector
- $\vec{r}$ position vector ção
- $\mathbf{R}$ rotation matrix
- $\vec{s}$



Euler

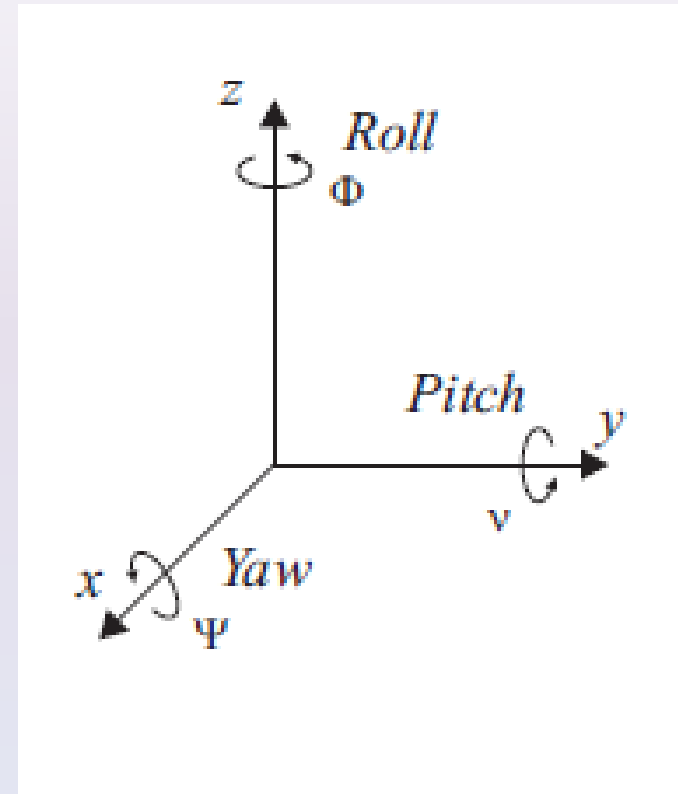
- Orientation of a system of orthogonal axes
- Cartesian reference
- Convention *x pfor Euler angles:*
 - First Rotation *Z* axis
 - Second *X'* axis
 - Third new *Z* $\Rightarrow$ *Z''* axis
- *There are other conventions*



$$R = R(z, \phi)R(x', \theta)R(z'', \psi)$$

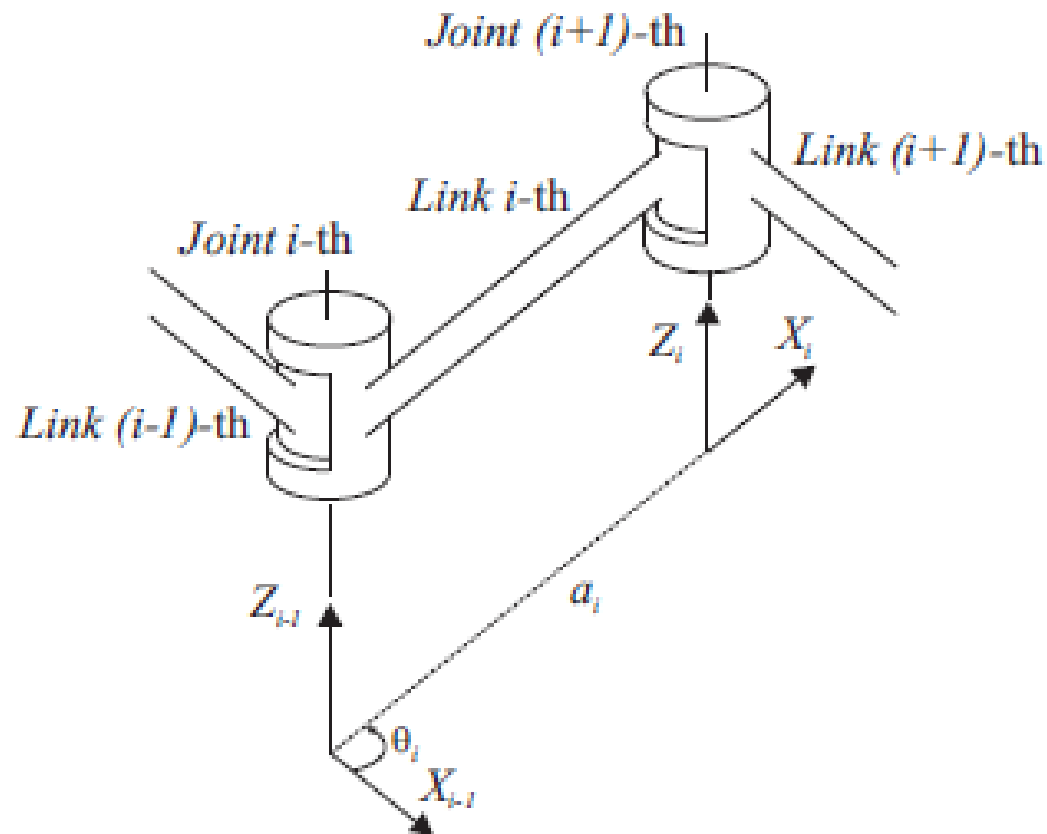
RPY

- Roll–Pitch–Yaw
- The orientation is divided in three rotations:
 - X
 - Y
 - Z





Denavit-Hartenberg





Denavit-Hartenberg

1. *Establish the base coordinate system $OX_0Y_0Z_0$ with Z_0 lying on the axis of motion of joint 1,*
2. *Establish the joint axis by aligning Z_i with the axis of motion of joint $i + 1$,*
3. *Establish the origin of the i -th coordinate system at the intersection of Z_i and Z_{i-1} or, if they are parallel, at the intersection of the common normal to Z_i and Z_{i-1} and Z_i .*
4. *Establish X_i axis at $X_i = \pm (Z_{i-1} \times Z_i) / \|Z_{i-1} \times Z_i\|$ or along the common normal between Z_i and Z_{i-1} if they are parallel.*
5. *Establish the Y_i at $Y_i = + (Z_i \times X_i) / \|Z_i \times X_i\|$ to complete the right-handed coordinate system.*



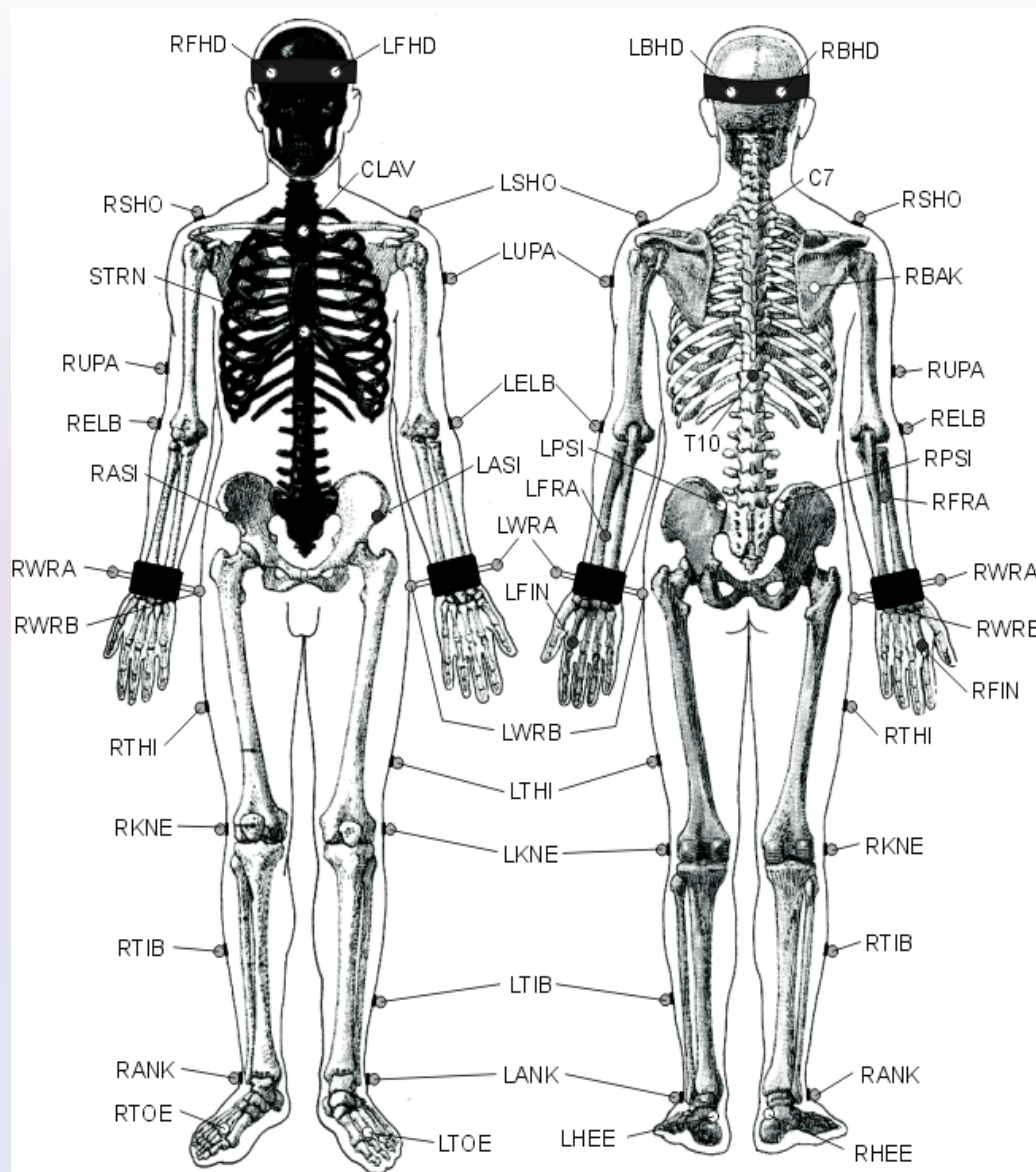
3. Human motion measurement

3.1. Motion measurement systems overview

- Optical systems
- EM systems
- Inertial systems

3.2. Motion estimation errors

- Model errors:
 - Wrong assumptions
 - Parameter errors
- Measurement errors



VICON. (OMG)
Plug-In-Gait



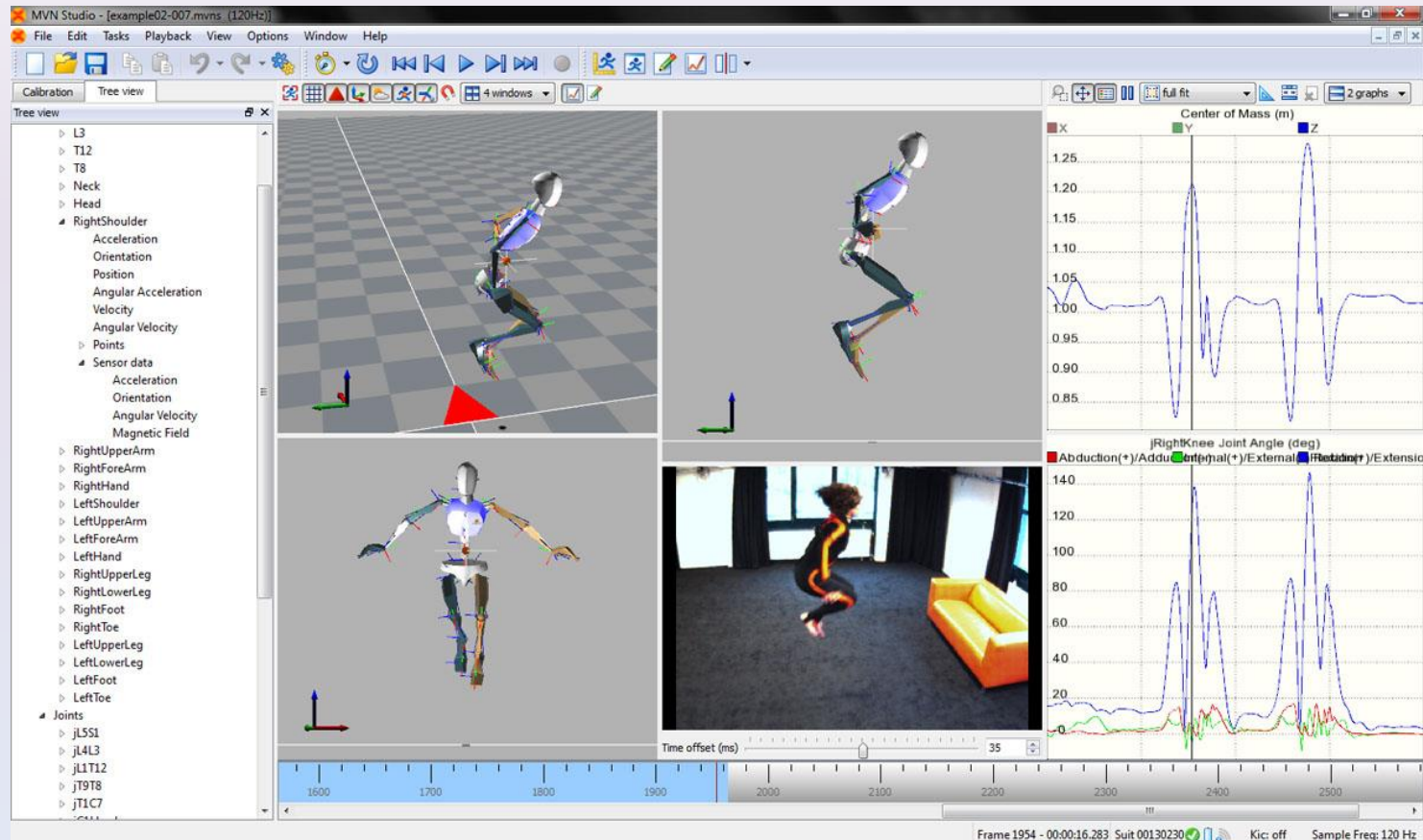
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Inertial systems



Inertial systems

- Integration drift
 - Kalman estimator application



Estimation errors

- Model errors:
 - Wrong assumptions
 - Rigid bodies
 - Measure over the tissues
 - Parameter errors
 - Inertial parameter estimation
 - Dimensions and position estimations (e.g. joint centers)
 - Are the parameters constant?
- Measurement errors:
 - Depend on the measurement system

Measurement errors

- Optical systems
 - Marker placement
 - Marker tracking
 - Marker movement on the soft tissue
- Inertial systems
 - Speed and acceleration integration errors (drift)
 - Magnetic interference errors
 - Attachment vibration



Movement description

Upper limb

- Medical description
- Model
- Technical description

Exemplo membro inferior

- Descrição médica
- Modelo
- Descrição técnica

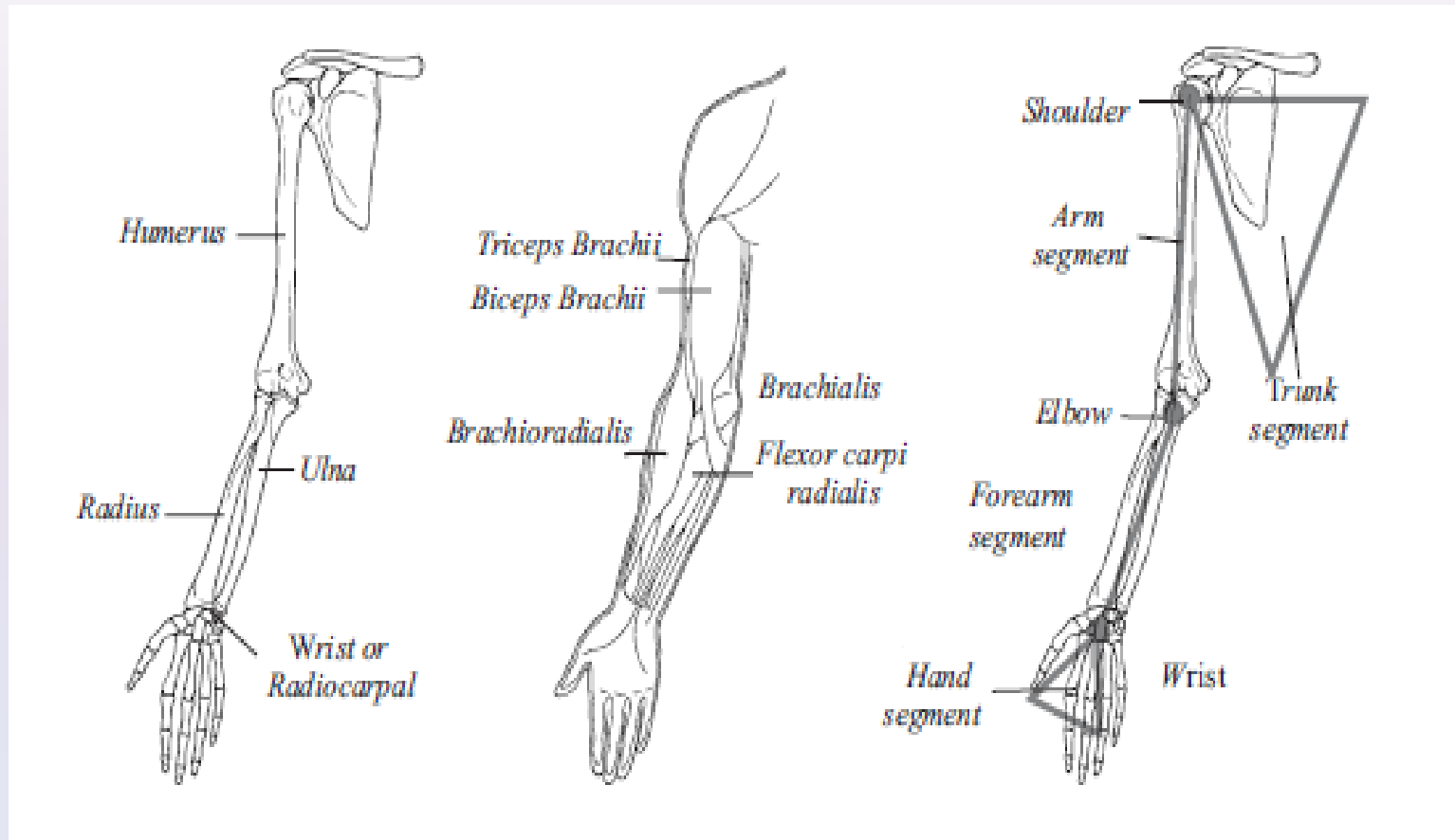


Upper limb

- Medical description
 - Joints
 - Bones
 - Muscles
- Model
 - Simplifications:
 - Joints considered depend on the application
 - Degrees of Freedom depend on the application
- Technical description:
 - Denavit -Hartenberg



Arm anatomy and segment model





Upper limb

- Joints:
 - Shoulder: Complex
 - Scapulo-thoracic plane, Acromio-clavicular
 - Glenohumeral
 - Elbow
 - Wrist
 - Hand and fingers
 - IS this complexity needed?



Shoulder. Simplified biomechanical model: 3DOF

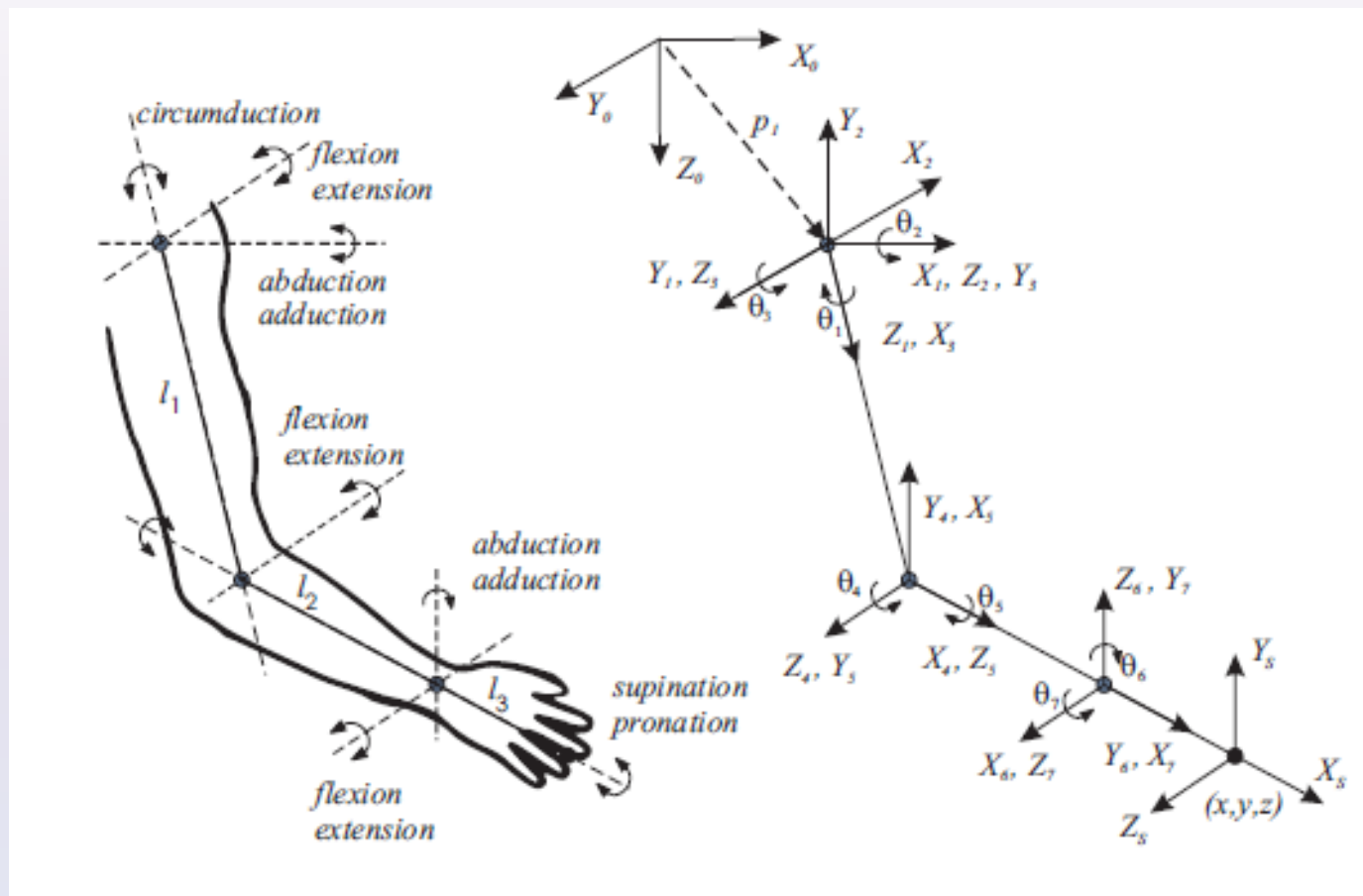
- *Flexion-extension.*
 - *Range of motion (ROM):*
 - *Flexion: 130 – 180°*
 - *extension: 30 – 80°*
- *Abduction – adduction*
 - *ROM*
 - *Abduction: 180 °*
 - *Adduction: 50°*
- *Rotation. (around humerus).*
 - *Internal Rotation (medial): 60-90°*
 - *External Rotation (lateral): 90°*
- The ROM for each DOF is large
- It can support the body weight

Elbow

- Elbow. Arm-forearm joint.
- Three joints: humero-ulnar, humero-radial and radio-ulnar.
- Simplification: 2 DOF : *Flexion-extension. Pronation-supination*
- *Flexion-extension:*
 - *Funcionamento como articulação de dobradiça*
 - ROM de 0 a 140-146°
 - ROM atividades diárias; 30-130°
 - Consideração: eixo de Rotation é oblíquo (inclinação lateral de 5 a 6 graus)
- *Pronation-supination.*
 - Definition from a 90° elbow flexion
 - *Pronation:* Max. 80°
 - *Supination:* Max 85°
 - Rotation axis crosses the radio-ulnar (proximal and distal) joints

Wrist

- Complex joint that can support high loads with high mobility
- Simplification to 2 DOF:
 - Flexion-extension: Intersubject variability
 - Flexion: 90°
 - extension: 80°
 - Abduction- adduction:
 - Abduction: 15°
 - Aduction: $30-40^{\circ}$





D-H parameters

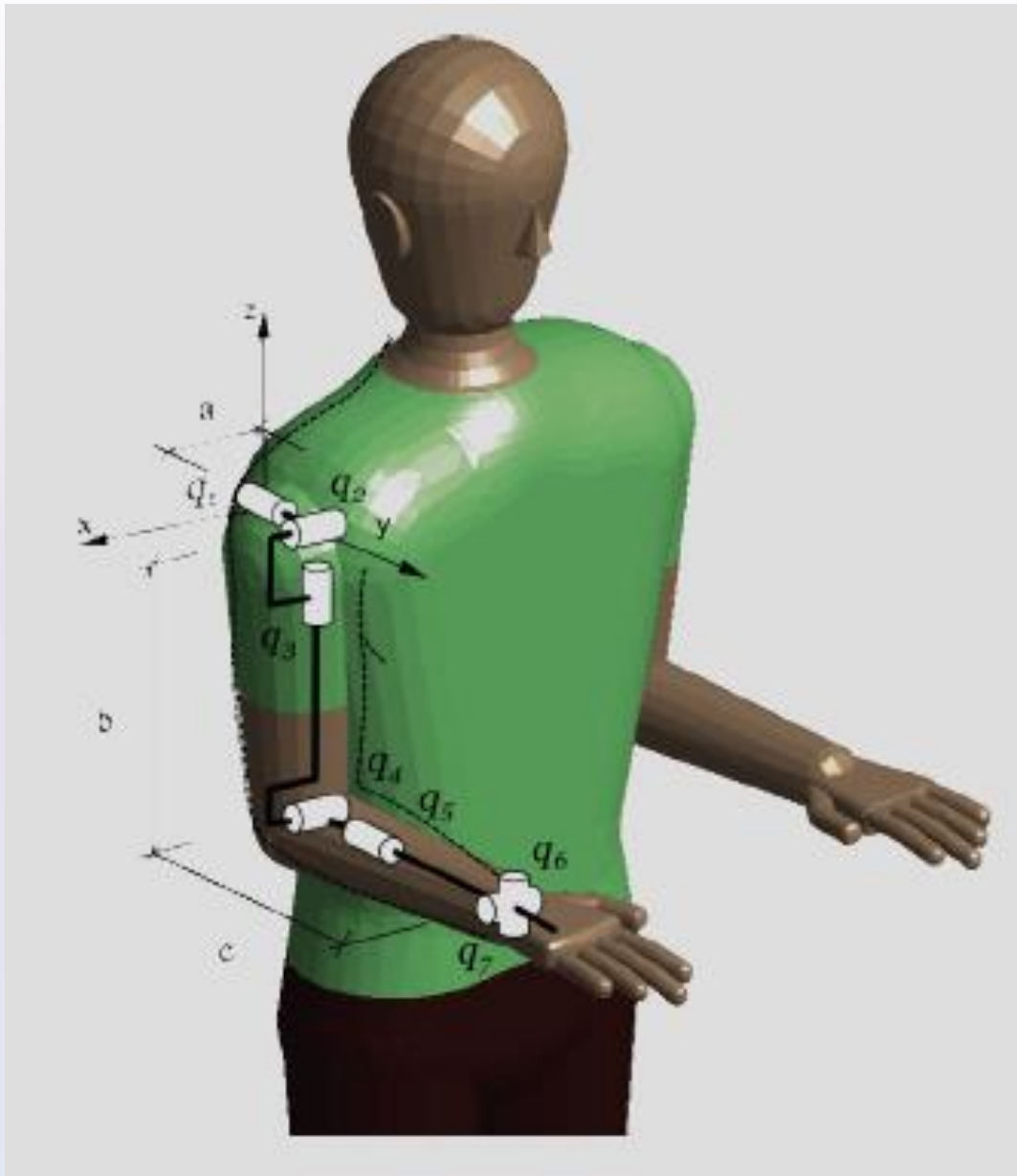
Table 3.1 D-H parameters for arms segments.

Joint	β_i	No.	α_i	a_i	d_i	θ_i
base	0	$1_{(0 \rightarrow 1)}$	0	a_0	d_0	0
shoulder	(-90) medial rot. / lateral rot. (+90)	$2_{(1 \rightarrow 2)}$	-90°	0	0	$\beta_1 + 90^\circ$
shoulder	(-180) abduction / adduction (+50)	$3_{(2 \rightarrow 3)}$	$+90^\circ$	0	0	$\beta_2 + 90^\circ$
shoulder	(-180) flexion / extension(+80)	$4_{(3 \rightarrow 4)}$	0	l_1	0	$\beta_3 + 90^\circ$
elbow	(-10) extension / flexion (+145)	$5_{(4 \rightarrow 5)}$	$+90^\circ$	0	0	$\beta_4 + 90^\circ$
elbow	(-90) pronation / supination (+90)	$6_{(5 \rightarrow 6)}$	$+90^\circ$	0	l_2	$\beta_5 + 90^\circ$
wrist	(-90) flexion / extension (+70)	$7_{(6 \rightarrow 7)}$	$+90^\circ$	0	0	$\beta_6 + 90^\circ$
wrist	(-15) abduction / adduction (+40)	$8_{(7 \rightarrow 8)}$	0	l_3	0	β_7

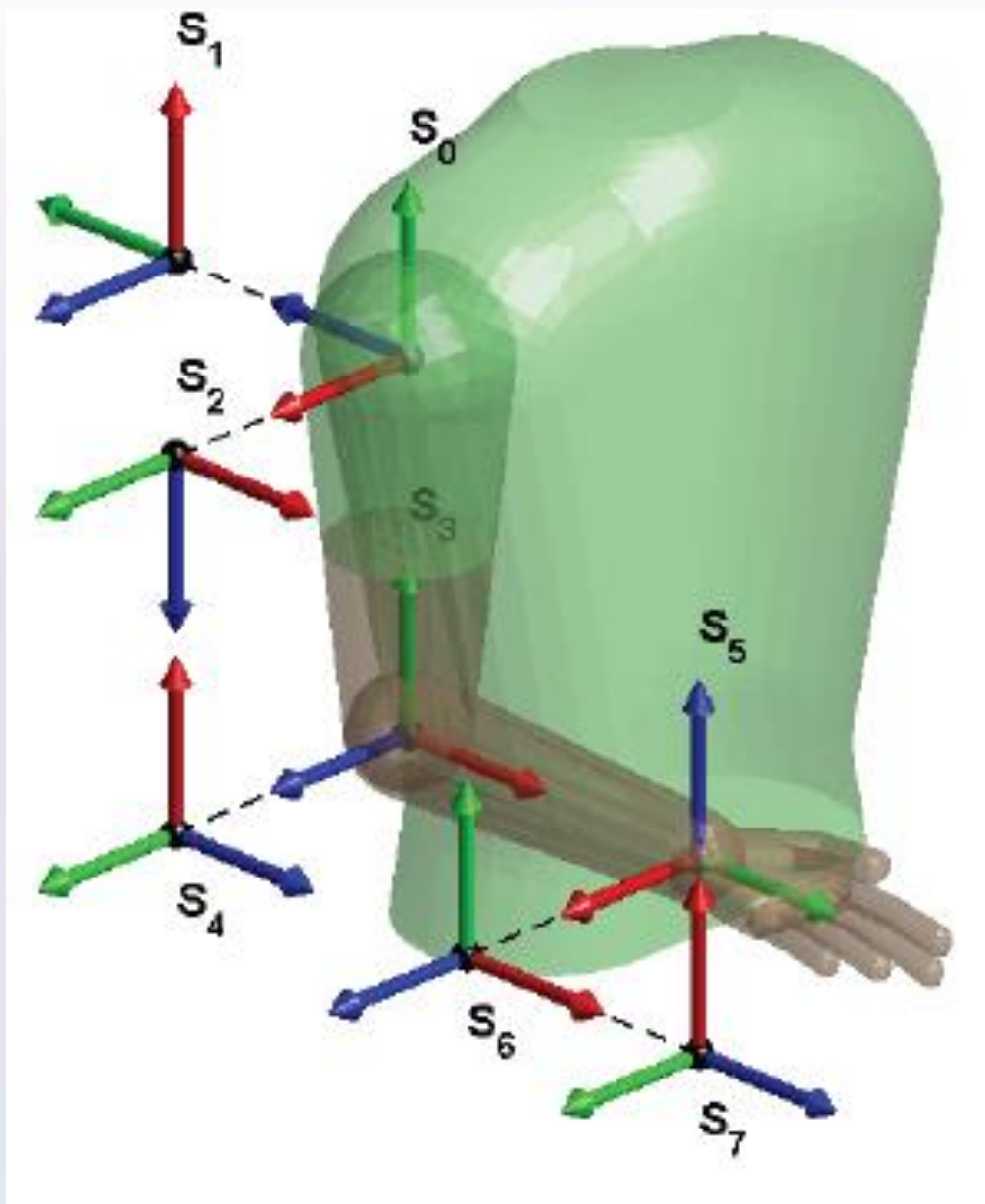


Anthropometrical data

Body segment	Length, L	Center of mass (% of L)	
		Proximal	Distal
upper arm	0.186 H	0.436	0.564
forarm	0.146 H	0.43	0.57
hand	0.108 H	0.506	0.494
thigh	0.245 H	0.433	0.567
leg	0.53 H	0.433	0.567
foot	0.152 H	0.5	0.5
HAT	0.475520 H	0.626	0.374



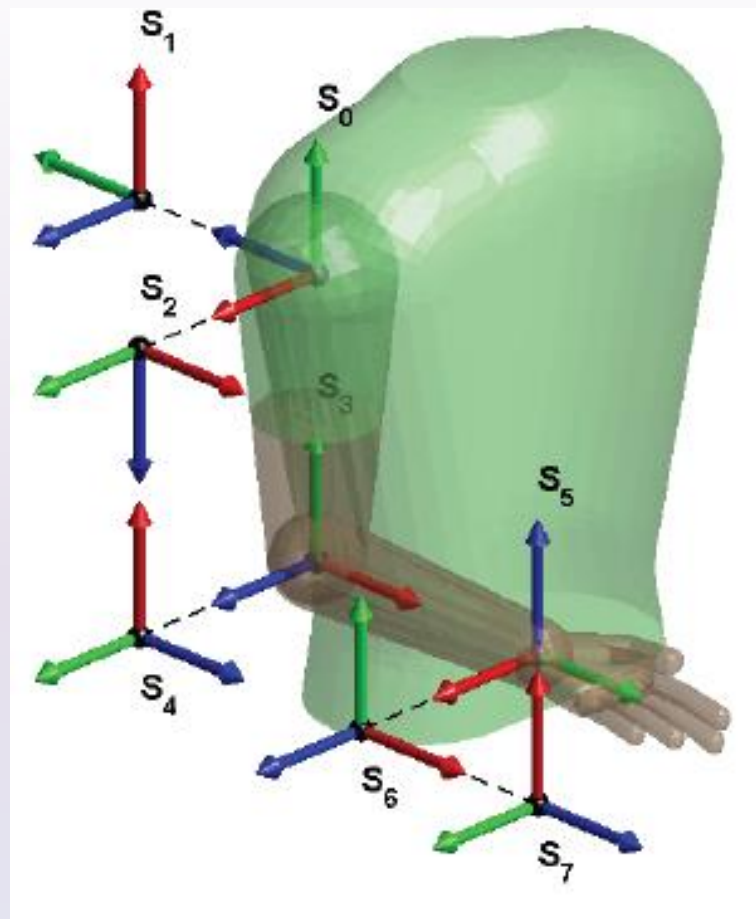
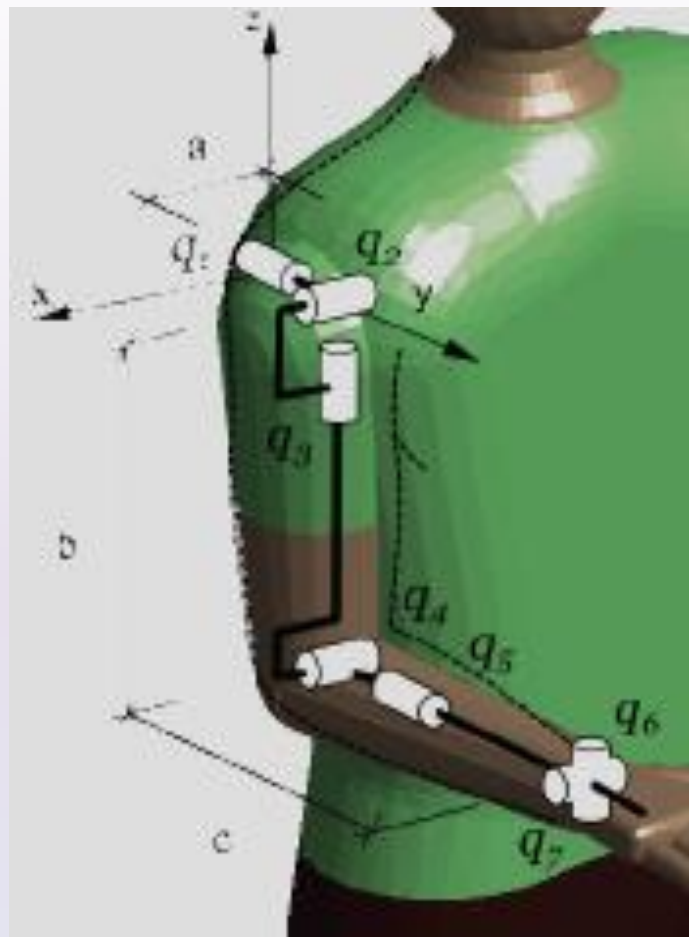
Bertomeu-Motos
et al, 2015. EMBC



Bertomeu-Motos
et al, 2015. EMBC

DH parameters of the arm

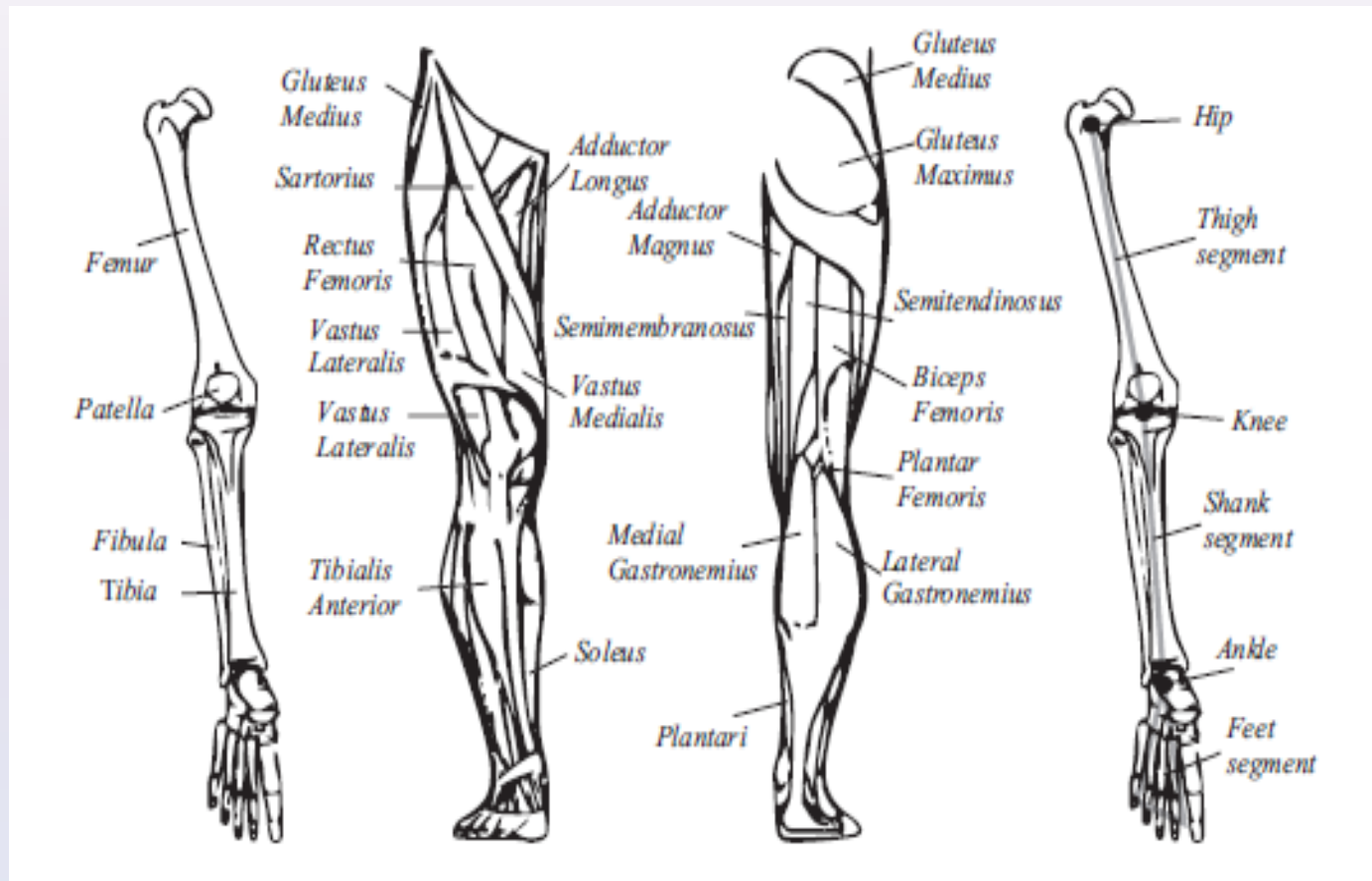
i	θ_i	d_i	a_i	α_i
1	$\pi/2 + q_1$	0	0	$\pi/2$
2	$3\pi/2 + q_2$	0	0	$\pi/2$
3	q_3	l_u	0	$-\pi/2$
4	$\pi/2 + q_4$	0	0	$\pi/2$
5	$\pi/2 + q_5$	l_f	0	$\pi/2$
6	$\pi/2 + q_6$	0	0	$\pi/2$
7	$\pi/2 + q_7$	0	0	$\pi/2$



i	θ_i	d_i	a_i	α_i
1	$\pi/2 + q_1$	0	0	$\pi/2$
2	$3\pi/2 + q_2$	0	0	$\pi/2$
3	q_3	l_u	0	$-\pi/2$
4	$\pi/2 + q_4$	0	0	$\pi/2$



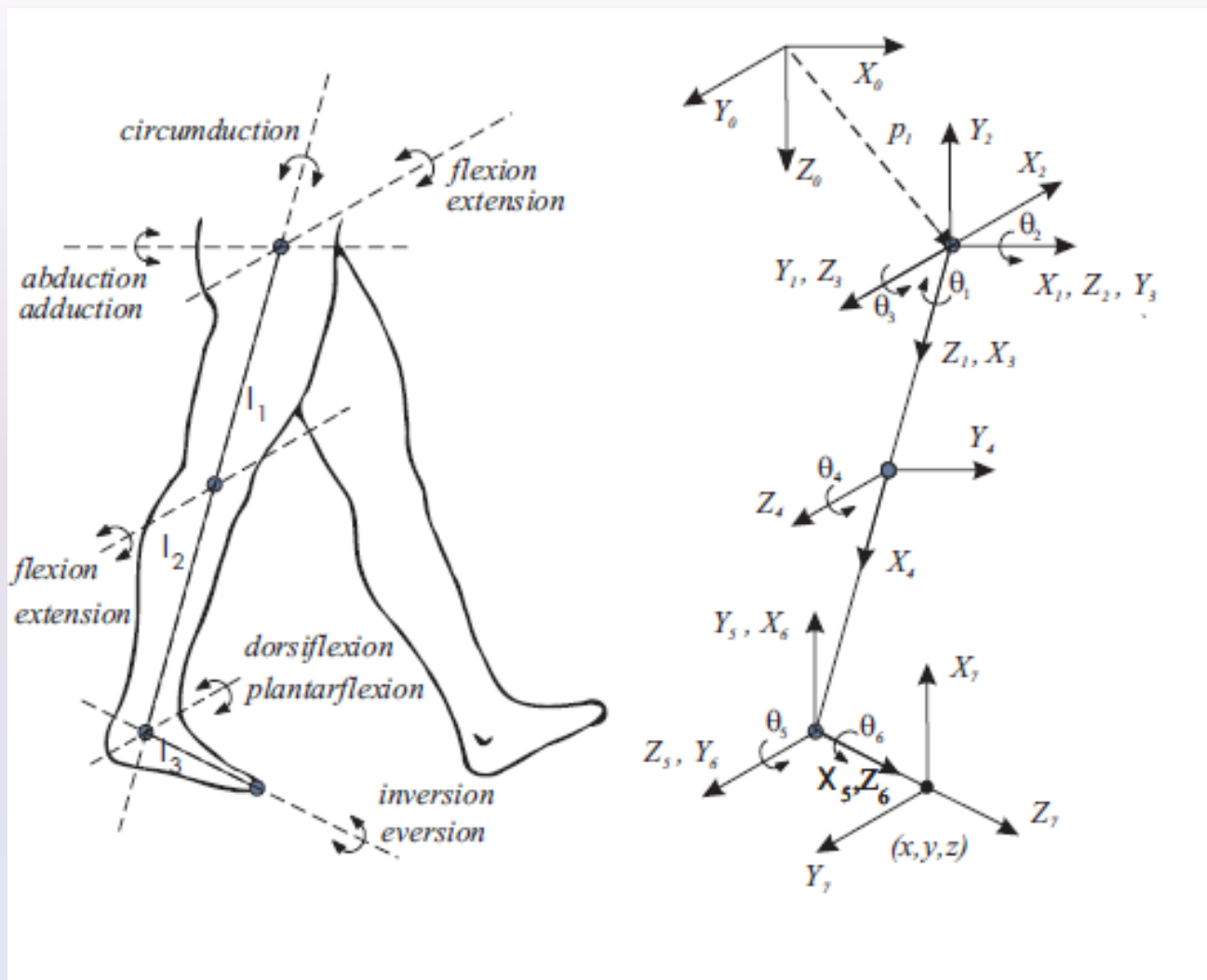
Leg anatomy



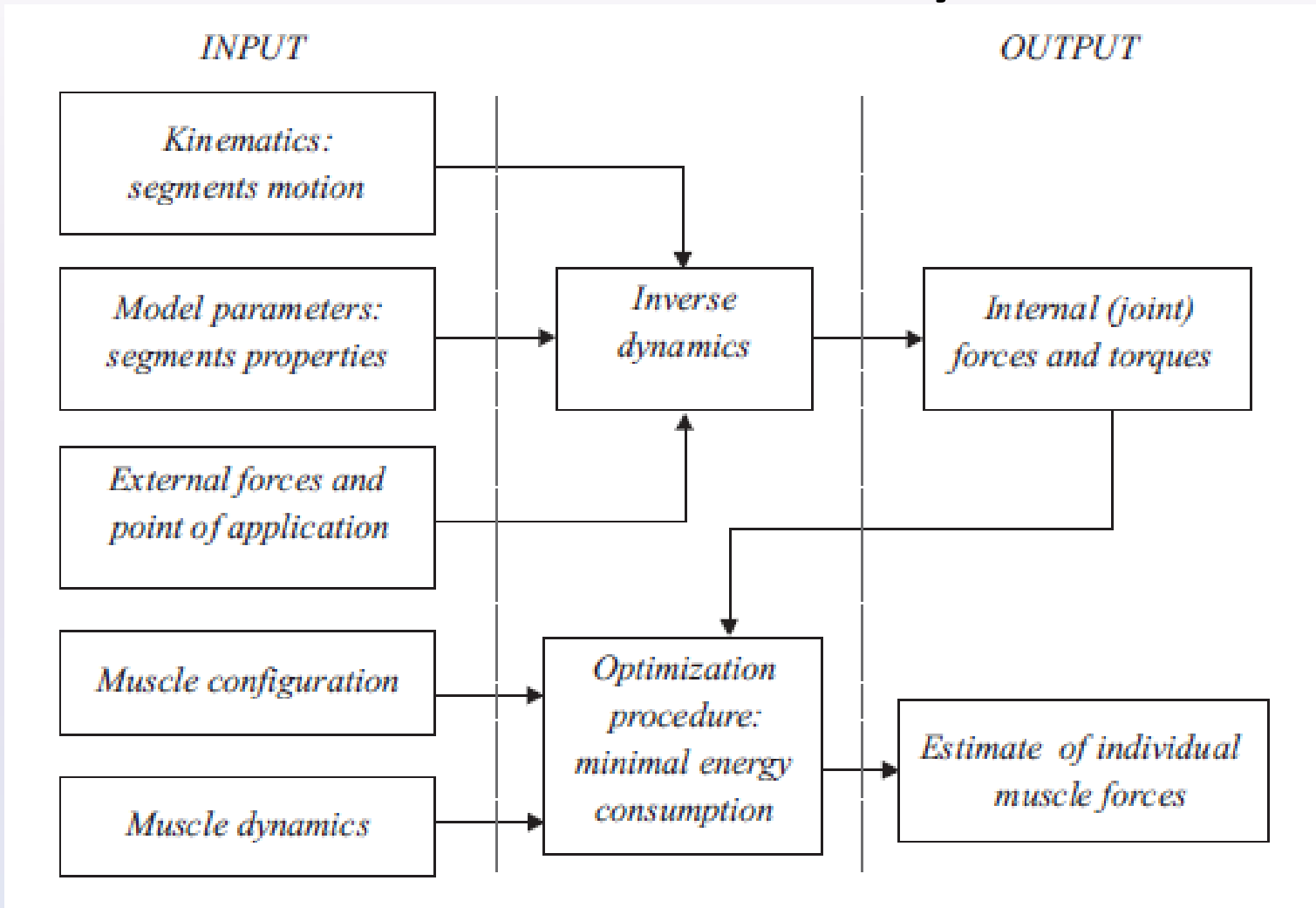


Membro inferior

- Joints:
 - Hip
 - Knee
 - Ankle
 - Foot: complex
 - Is it needed?

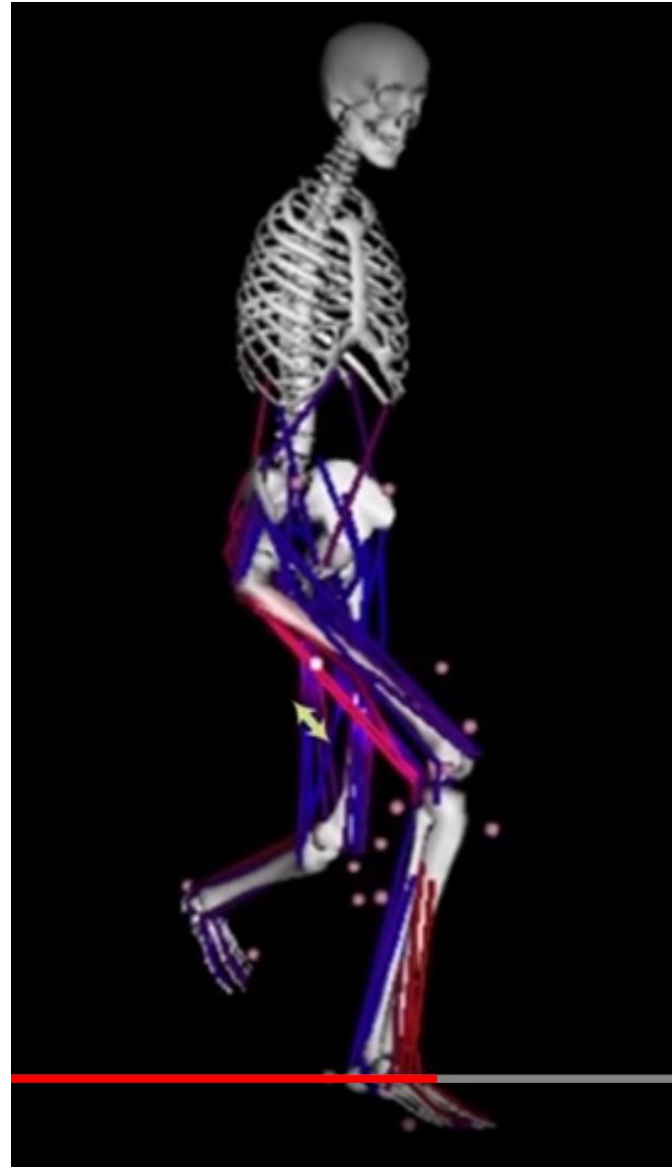


5. Direct and inverse dynamics



$$\mathbf{M}(\vec{q})\ddot{\vec{q}} + \mathbf{C}(\vec{q}, \dot{\vec{q}}) + \mathbf{K}(\vec{q}) = \vec{\tau}$$

OpenSim





- Thank you for your attention

Project definition

Example