ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

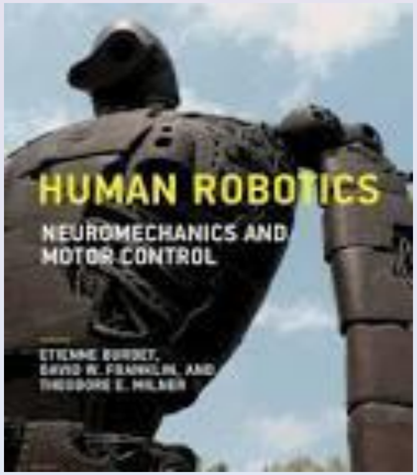
Basic concepts of anatomy and mechanical modelling of the human body

Arturo Forner-Cordero

(aforner@usp.br)

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. 4^{th} 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).

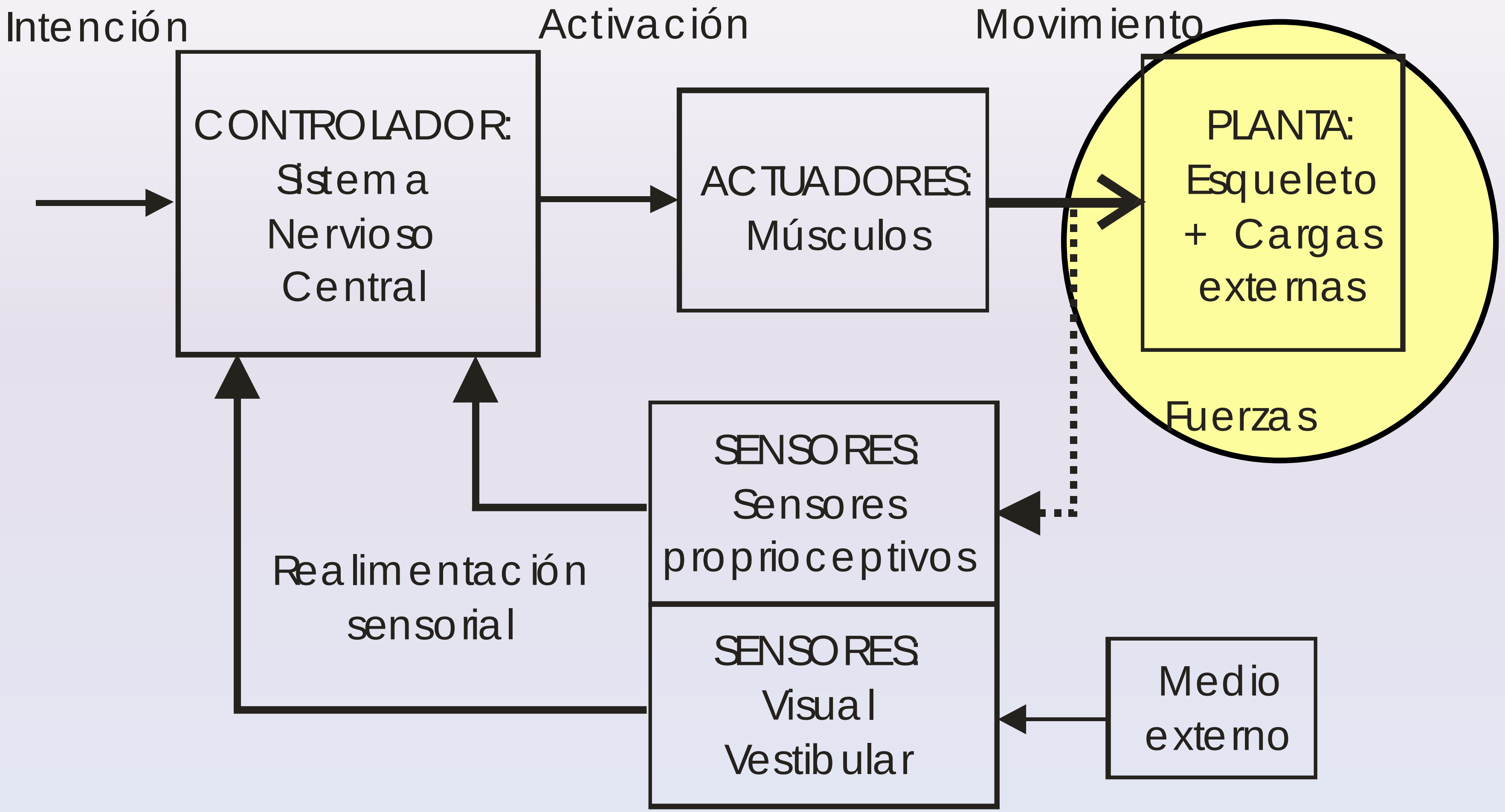
ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Bibliography

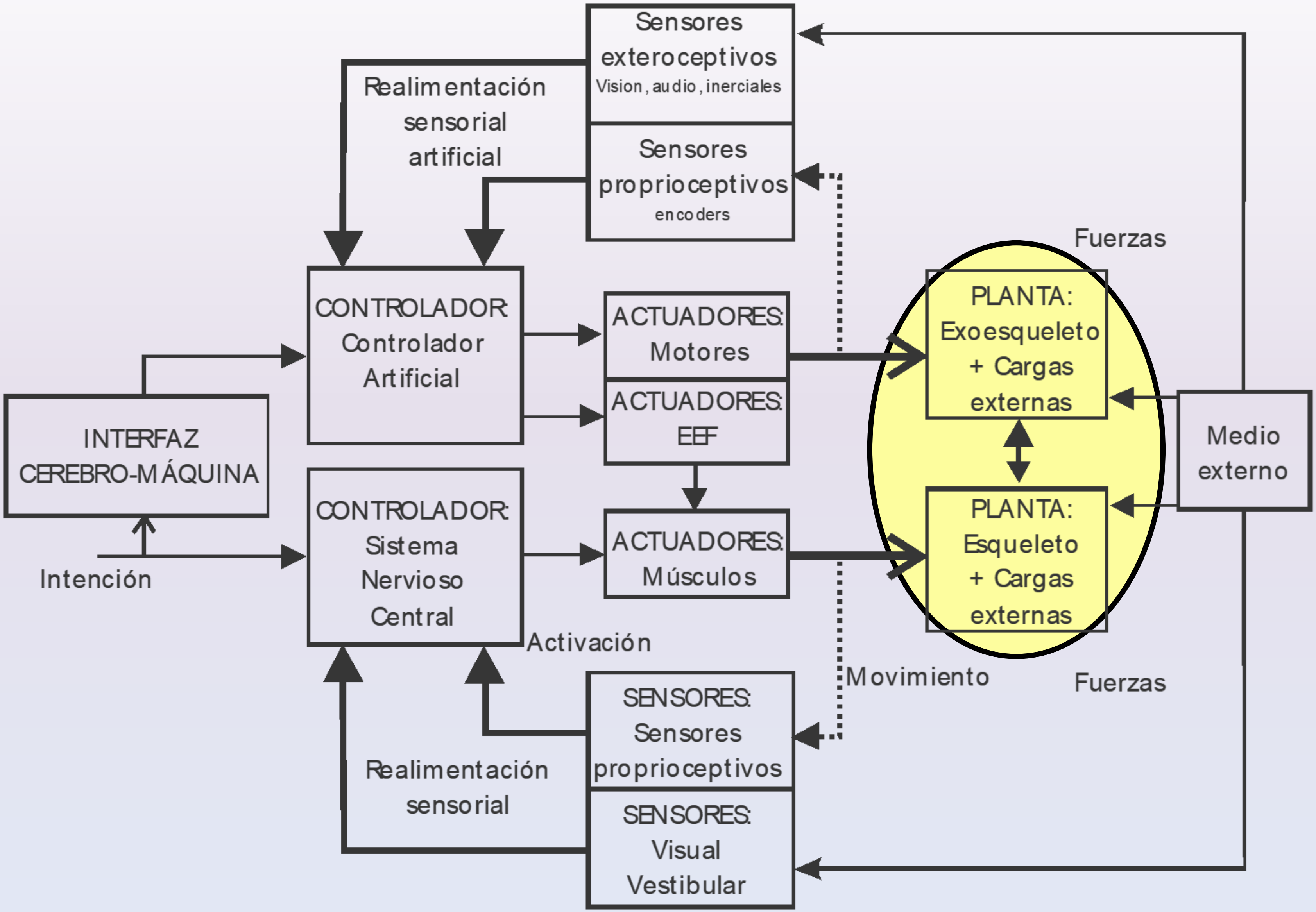
- Chapter 3. Kinematics and dynamics of wearable robots. A. Forner–Cordero, J.L. Pons, E.A. Turowska. In: Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.
- Modelling and Control of Robot Manipulators. Sciavicco, L., B. Siciliano. Springer-Verlag. 2005.
- 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.*

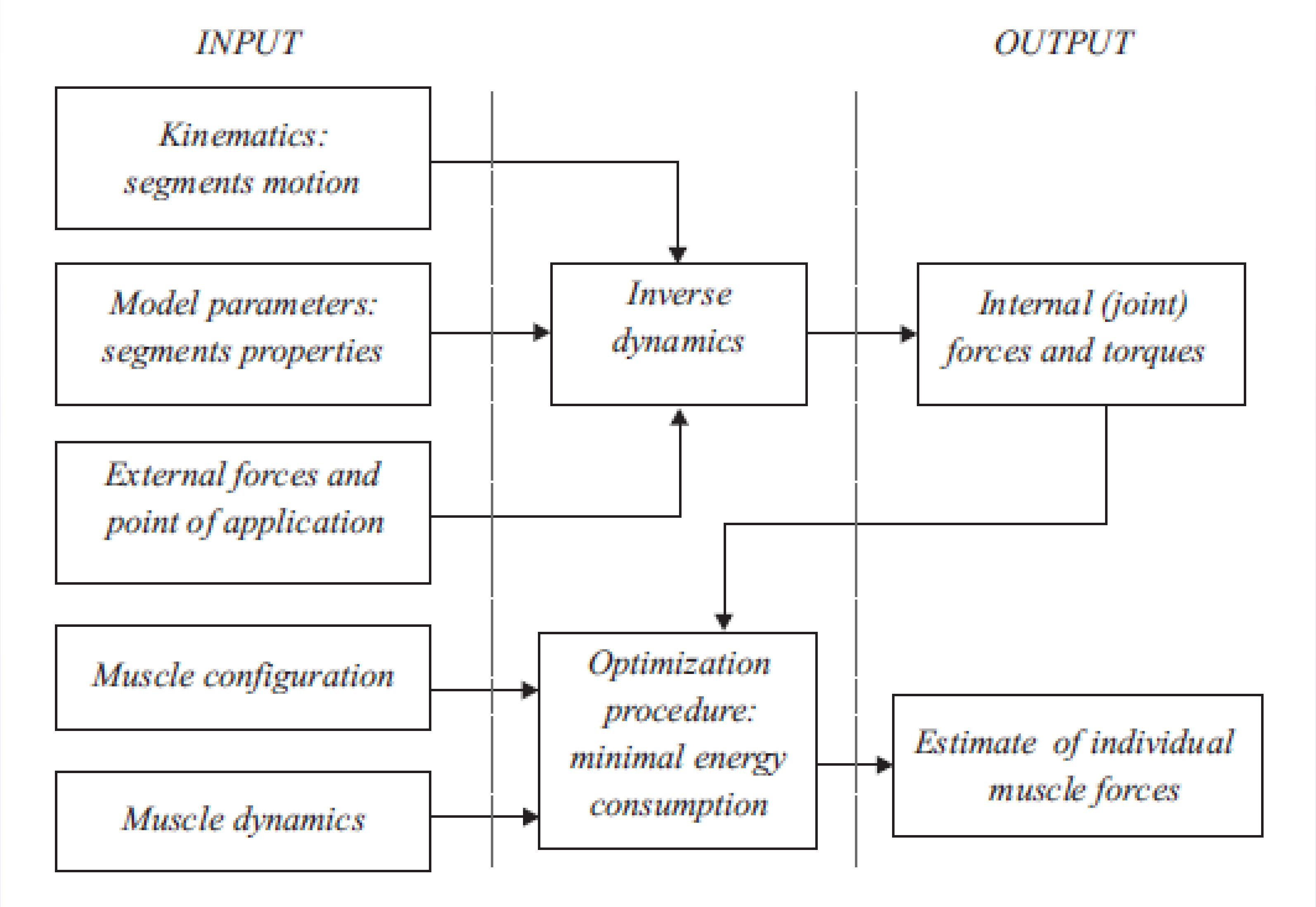
ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Human motor system



Human-robot motor system





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.

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. Aplication: Inverse dynamics analysis

1. Modelling of the human movement

1.1. Motor system structures

1.2. Assumptions

1.3. Rigid body dynamics

Segment model

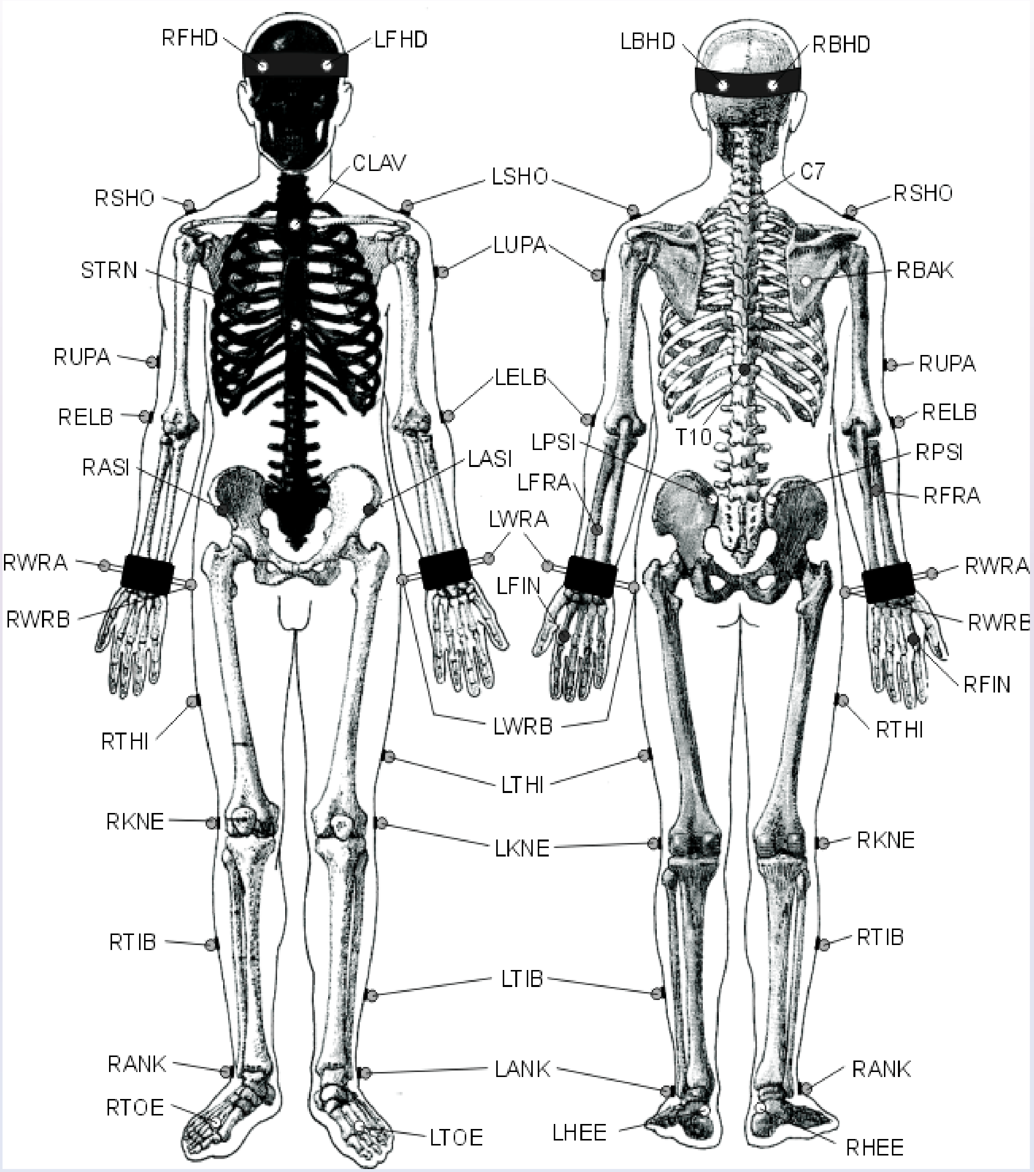
Motor system structures

Anatomical structure

High stiffness tissues	Low stiffness tissues
Bones: skeleton	Orgnas, muscles

Mechanical system

Segments	Joints	Actuators



VICON. (OMG)
Plug-In-Gait

Assumptions

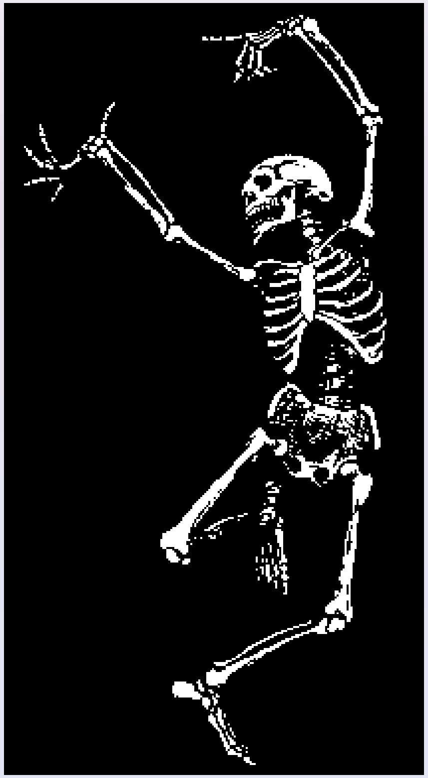
- Biomechanical modelling:
  - Assumptions:
    - Rigid bodies: bones
    - Deformations occur only at the joints
    - System of rigid bodies
  - Tissue deformations:
    - Finite Element analysis
  - Inverse dynamics analysis

Rigid body dynamics

- Movement description: kinematics
- Forces description: dynamics
- Link or segments model
  - How to define it?
  - What information is needed?
    - Nº 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
  - Nº 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

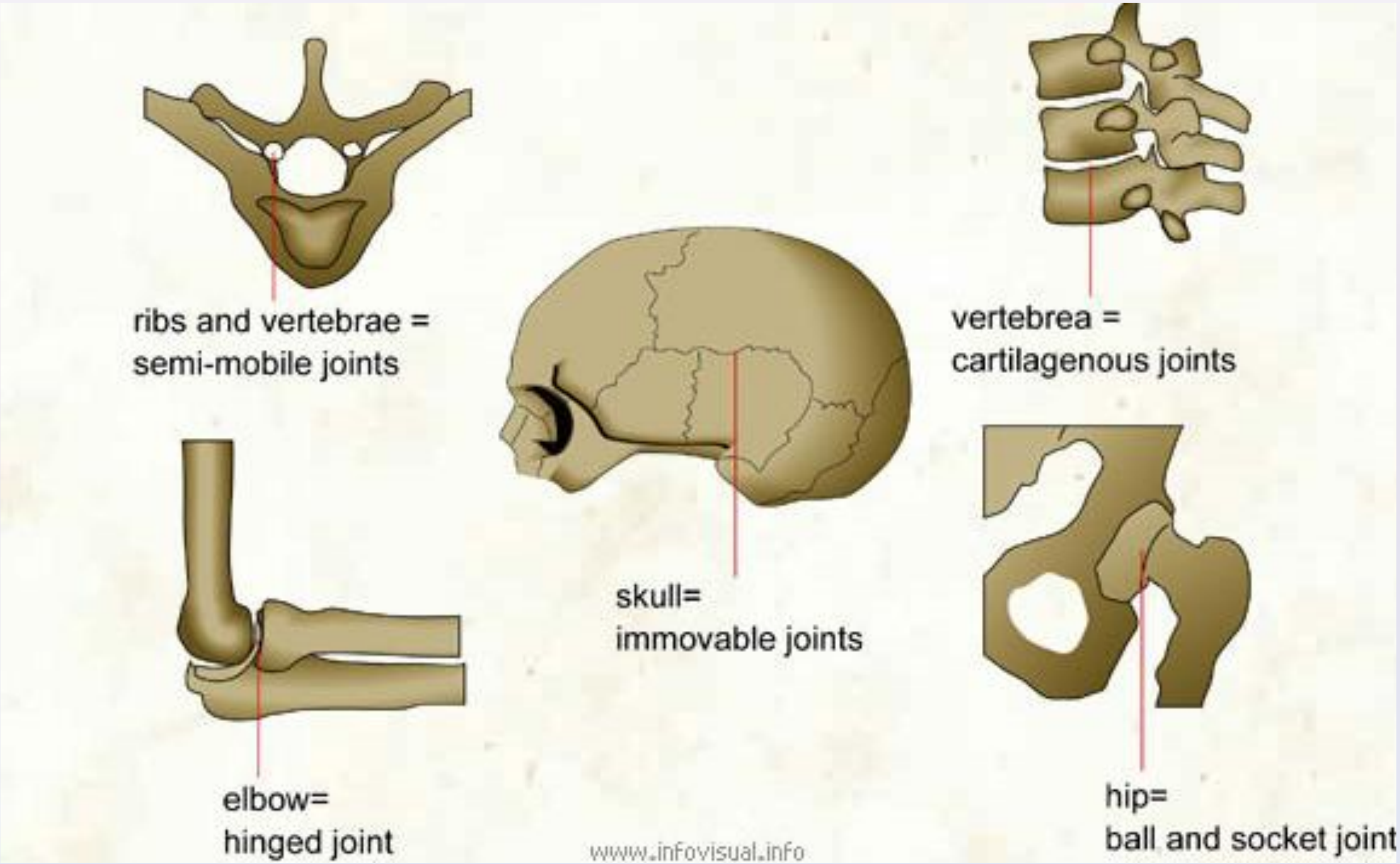
2.1. Medical description:

- Joints
- Movement planes
- Movement description

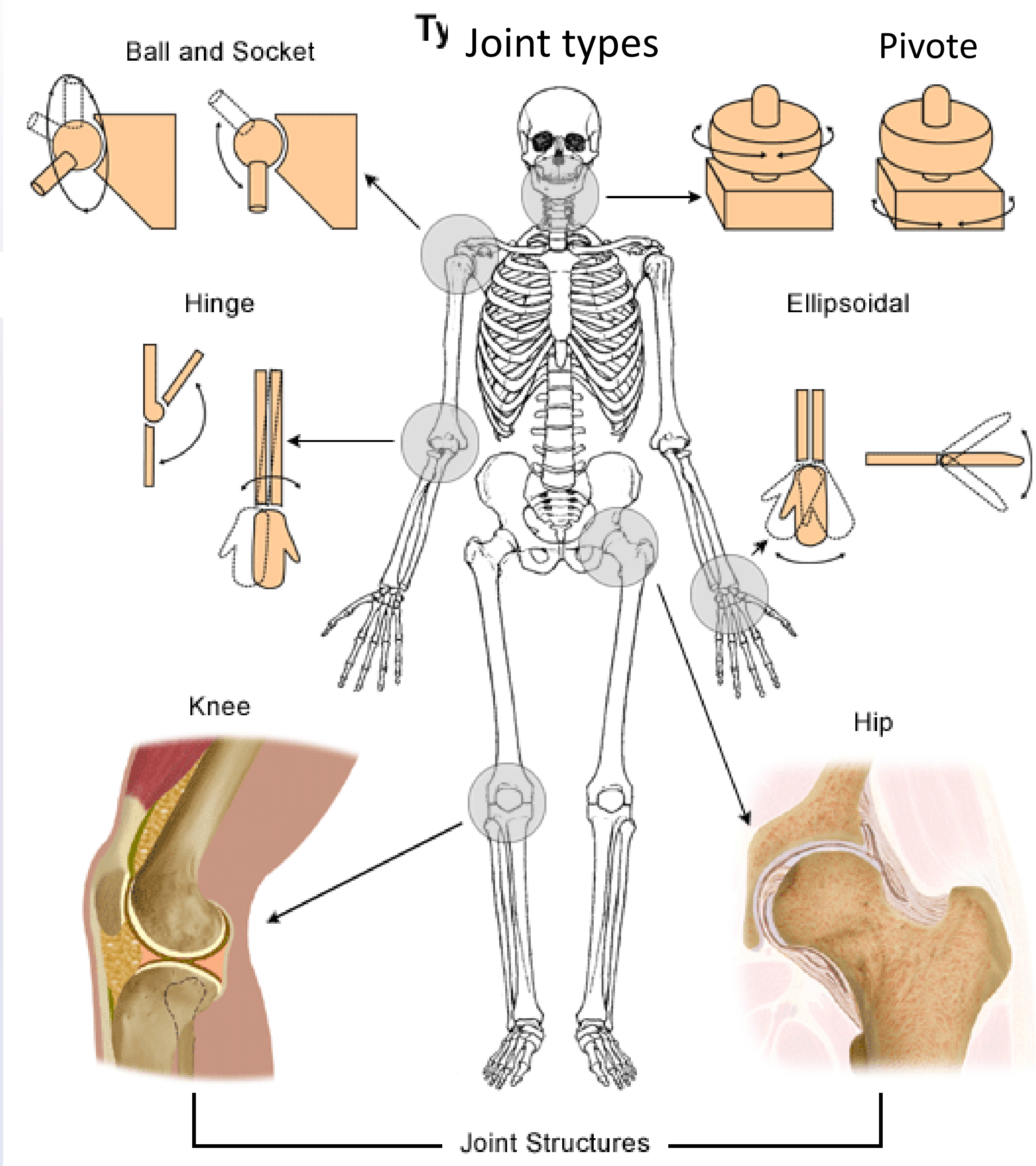
2.2. Technical description:

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

Joint types


ribs and vertebrae =
semi-mobile joints
vertebrea =
cartilagenous joints
skull=
immovable joints
elbow=
hinged joint
hip=
ball and socket joint
www.infovisual.info

ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO



Dobradiça

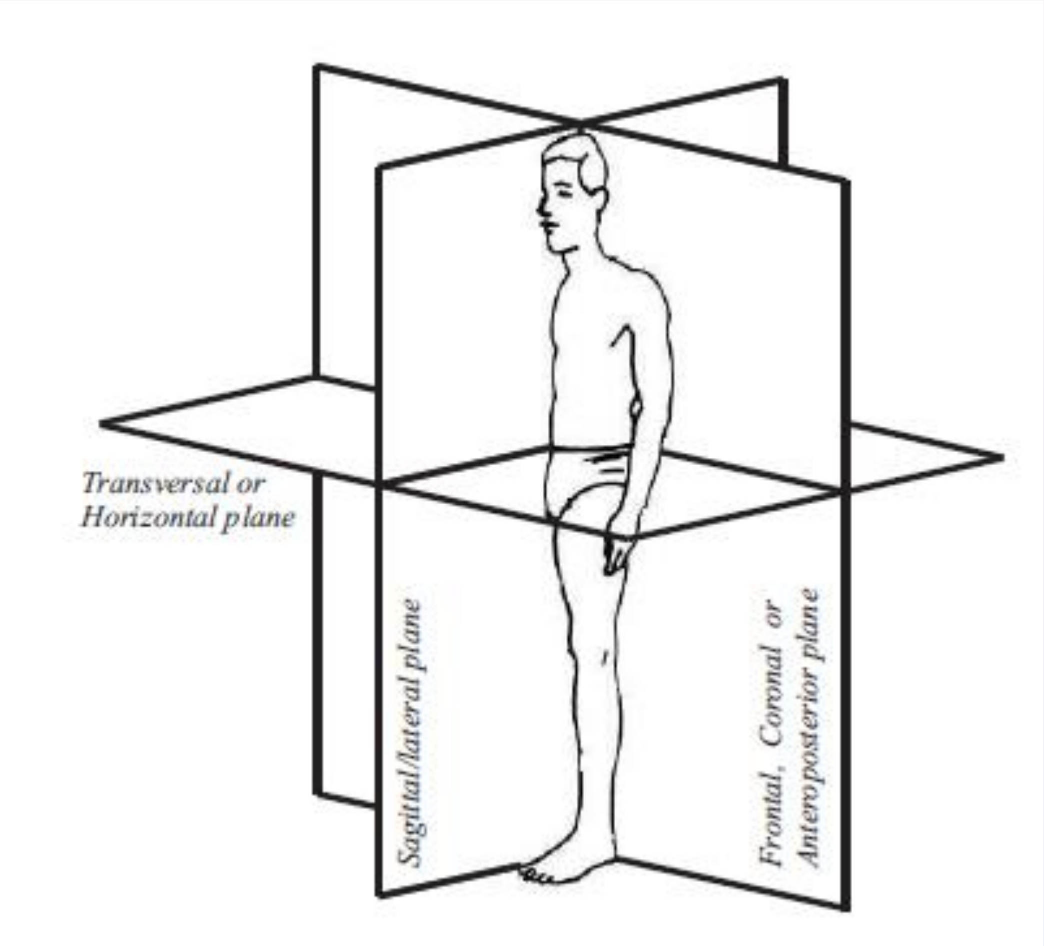
Elipsoidal

Joelho

Quadril

Columbia University Medical Center

Anatomical planes

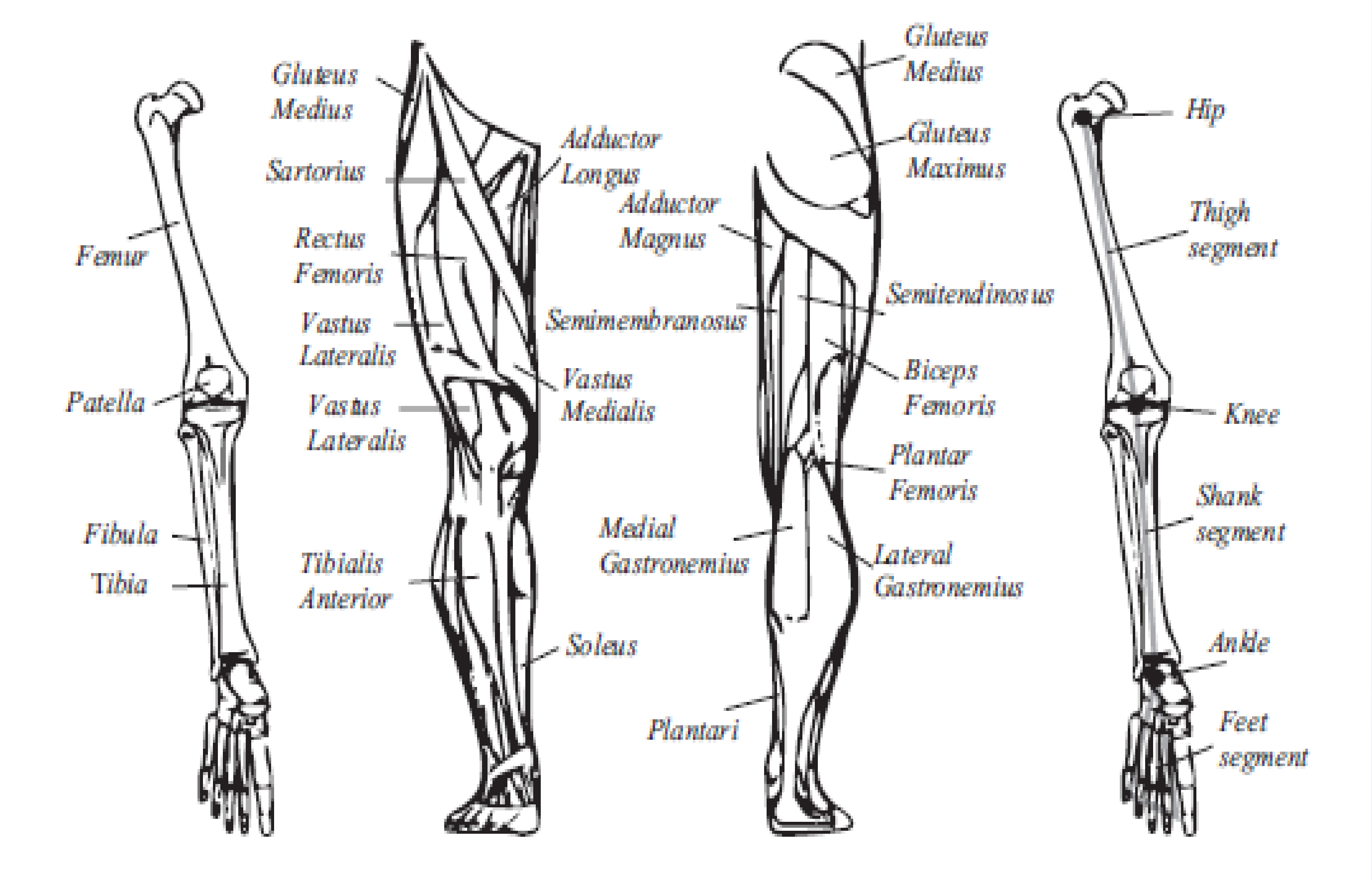


Chapter 3. Kinematics and dynamics of wearable robots. A. Forner–Cordero et al. In: Wearable Robots: Biomechatronic Exoskeletons. Editor: J. L. Pons (2008) John Wiley & Sons, Ltd.

Planos anatómicos

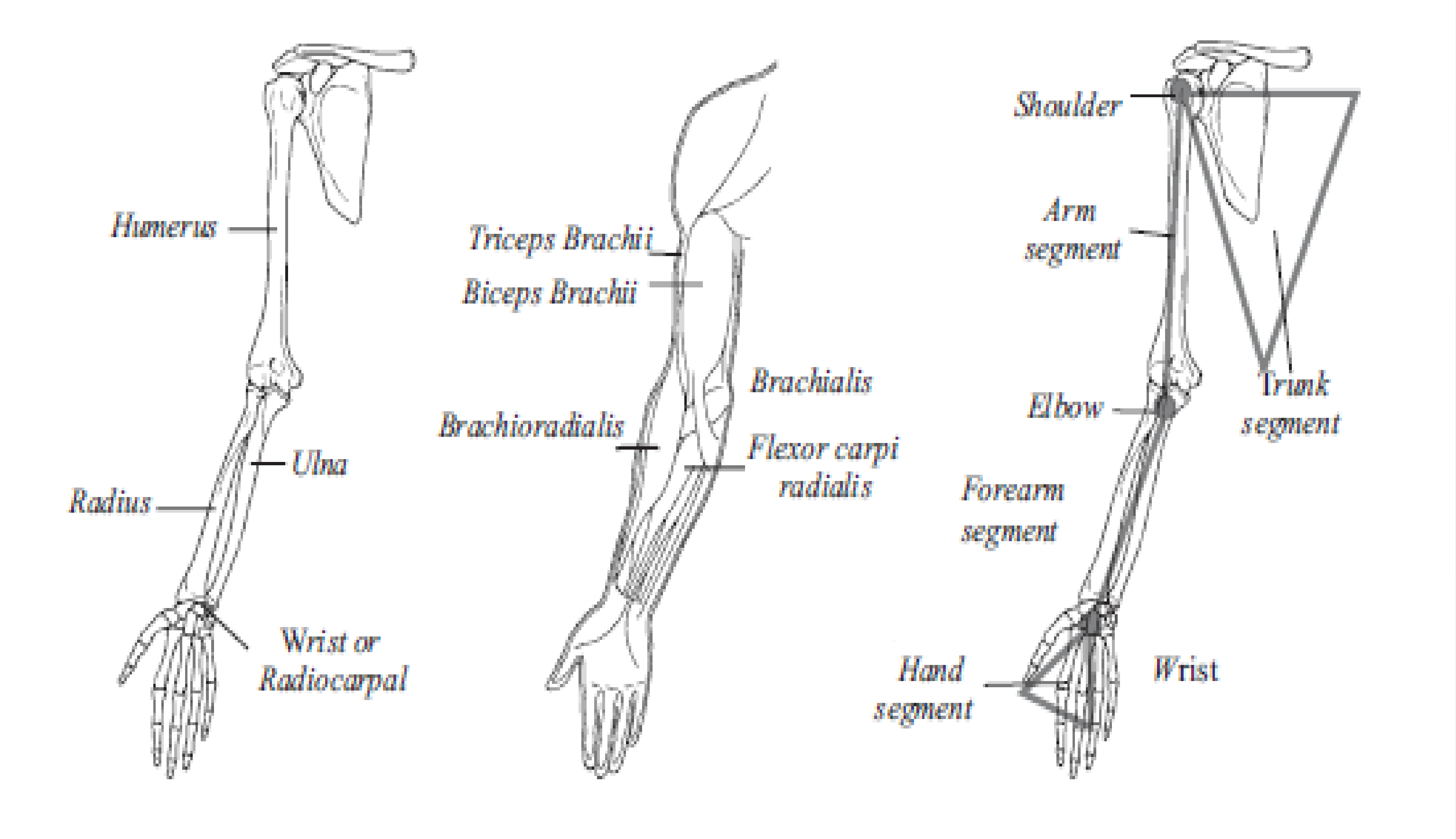
- *Frontal or coronal plane:*
  - *Divides the body in anterior and posterior sides*
- *Transversal plane:*
  - *Divides the body in superior and inferior parts*
- *Sagital or lateral plane*
  - *Divides the body in right and left sides*

Leg anatomy



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.

Arm anatomy and segments model



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.

Medical description of movement

- Sagital 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:

- ***Ab****duction* limb motion away from the medial plane of the body; *(ab -> away)*
- ***Ad****uction* limb motion towards the medial plane of the body;
  - Oposite of abdu*ction*.

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

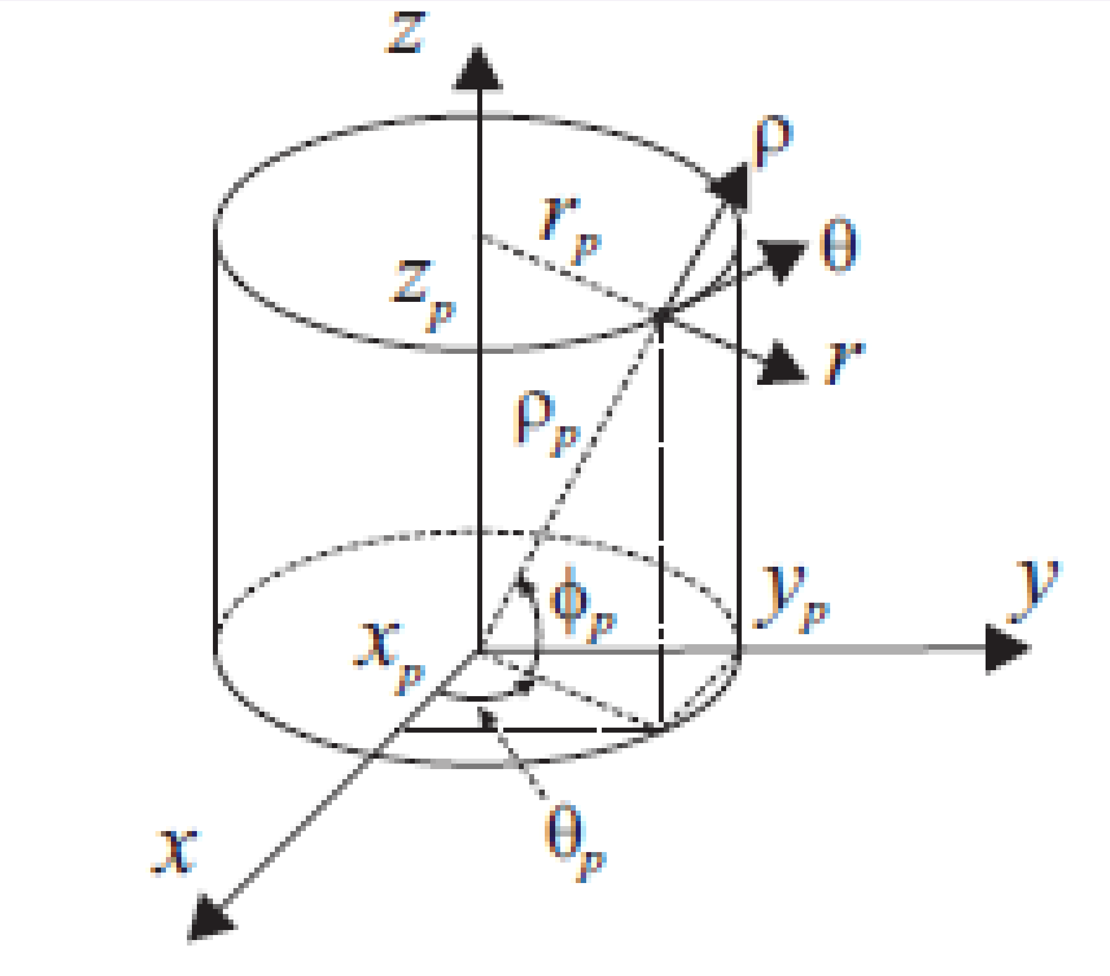
- Pathology description and assessment
- Ambiguity:
  - Movement around several axes
  - Combinations of rotations and translations
  - No clear rules to define the order of rotations
  - The planes and axis rotate with the movement?
    - Elbow flexion with the shoulder in abduction…
- CONCLUSION: This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

Technical description of movement. Kinematics

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

ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Technical description of movement



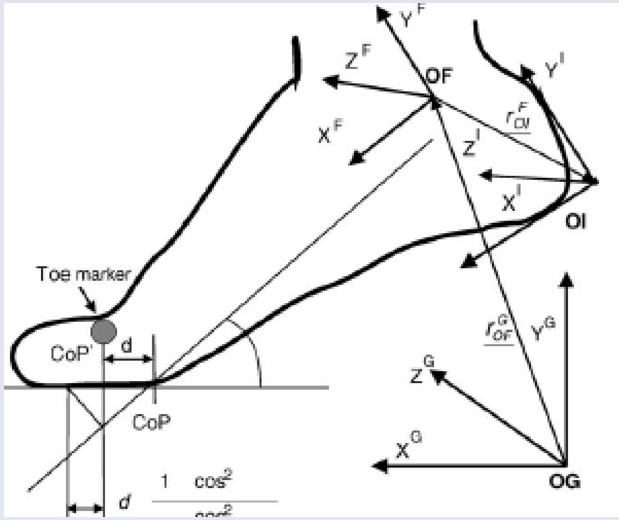
Rotation matrix and position vector

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

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

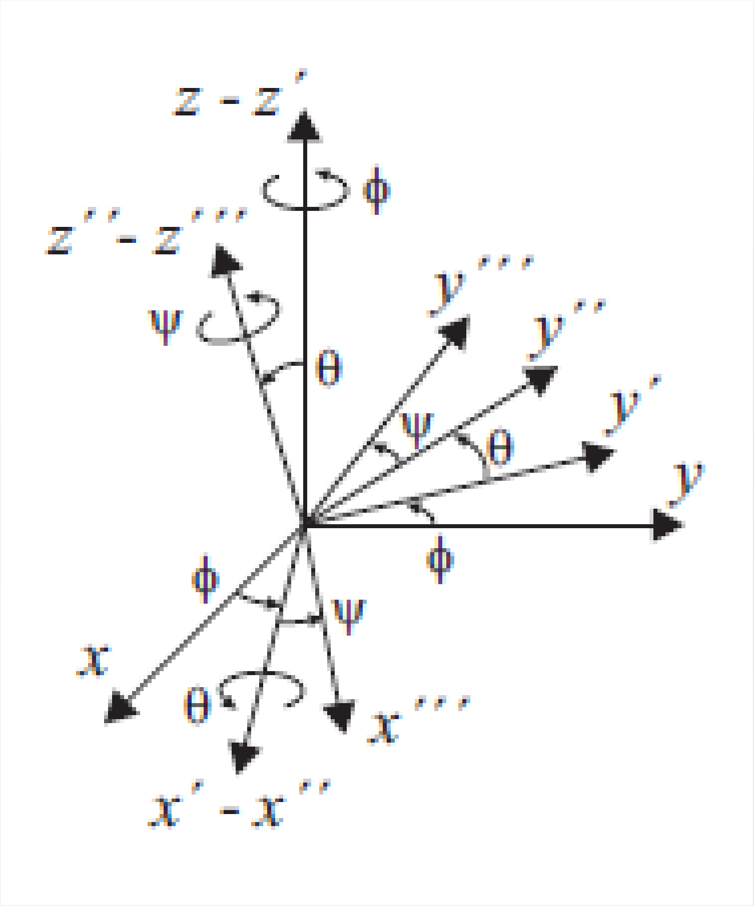
$$\mathrm{R}^{-1} = \mathrm{R}^{\mathrm{T}}$$

- $\bar{p}$ origin position vector
- $\bar{r}$ position vector ção
- **R** rotation matrix
- $\bar{s}$



Euler

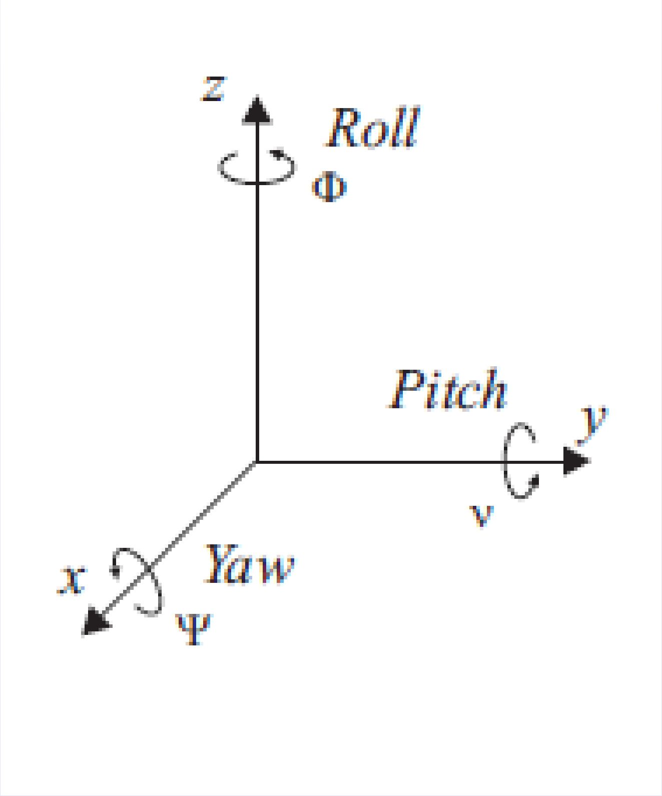
- Orientation of a system of orthogonal axes
- Cartesian reference
- Convention *x pfor Euler angles:*
  - *First Rotation Z axis*
  - *Second X' axis*
  - *Third new Z => Z'' axis*
- *There are other conventions*



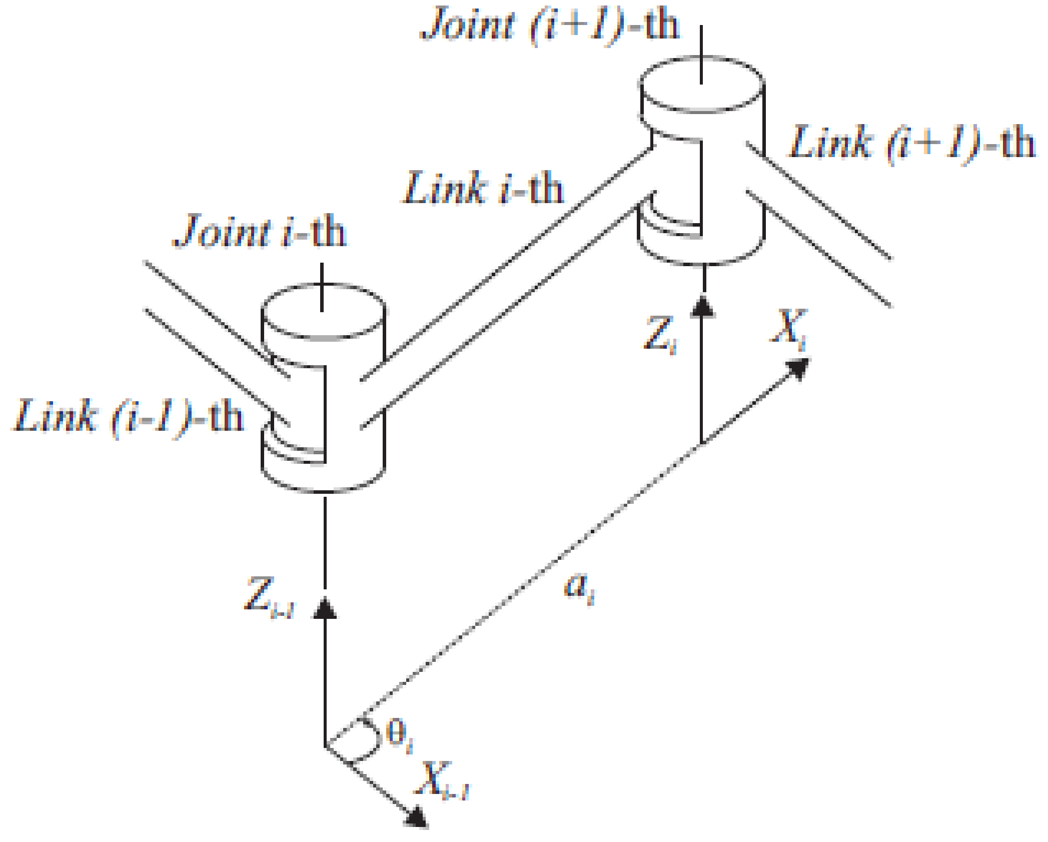
$$R = R(z, \phi) R(x', \theta) R(z'', \psi)$$

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.

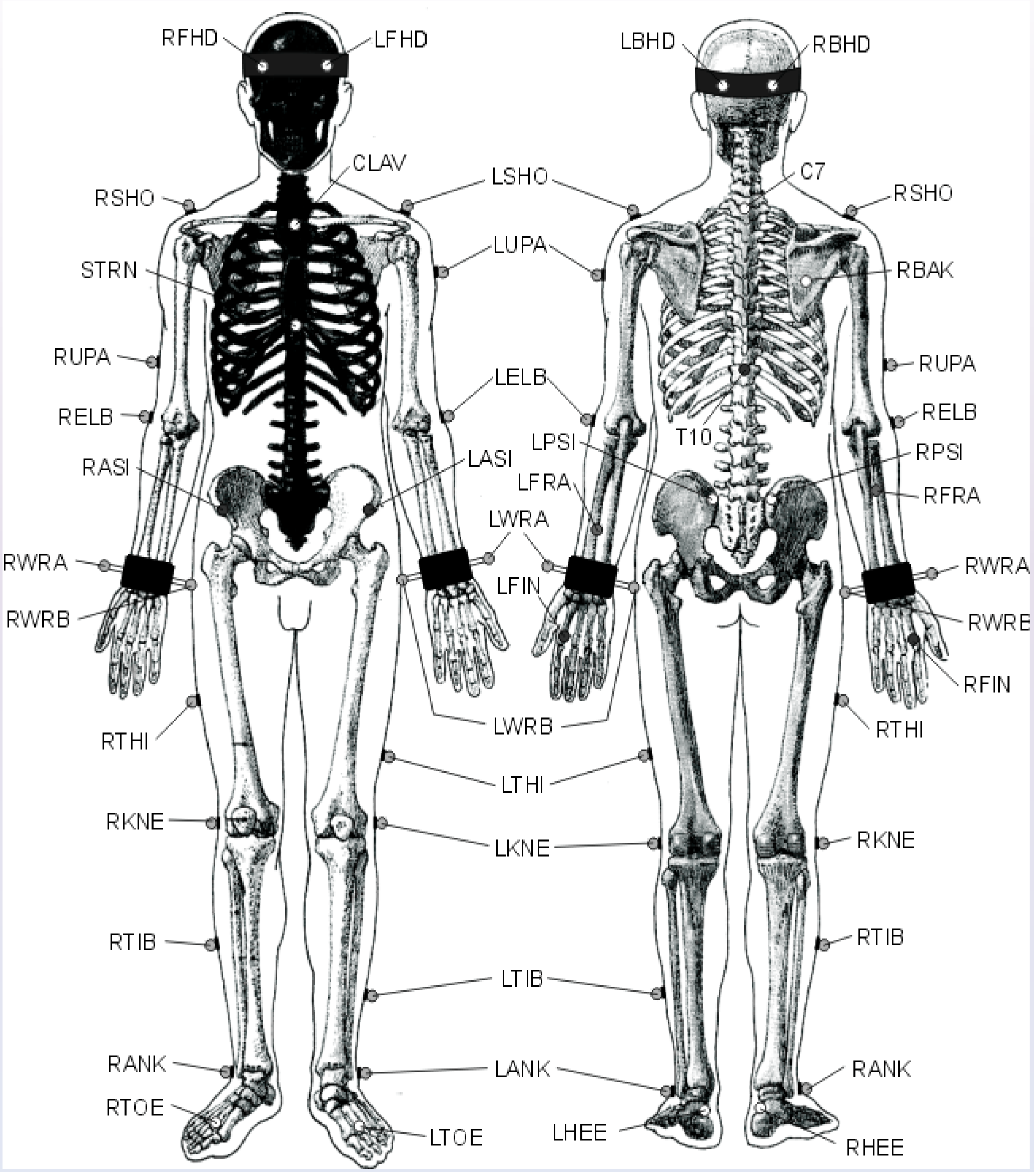
3. Human motion measurement

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

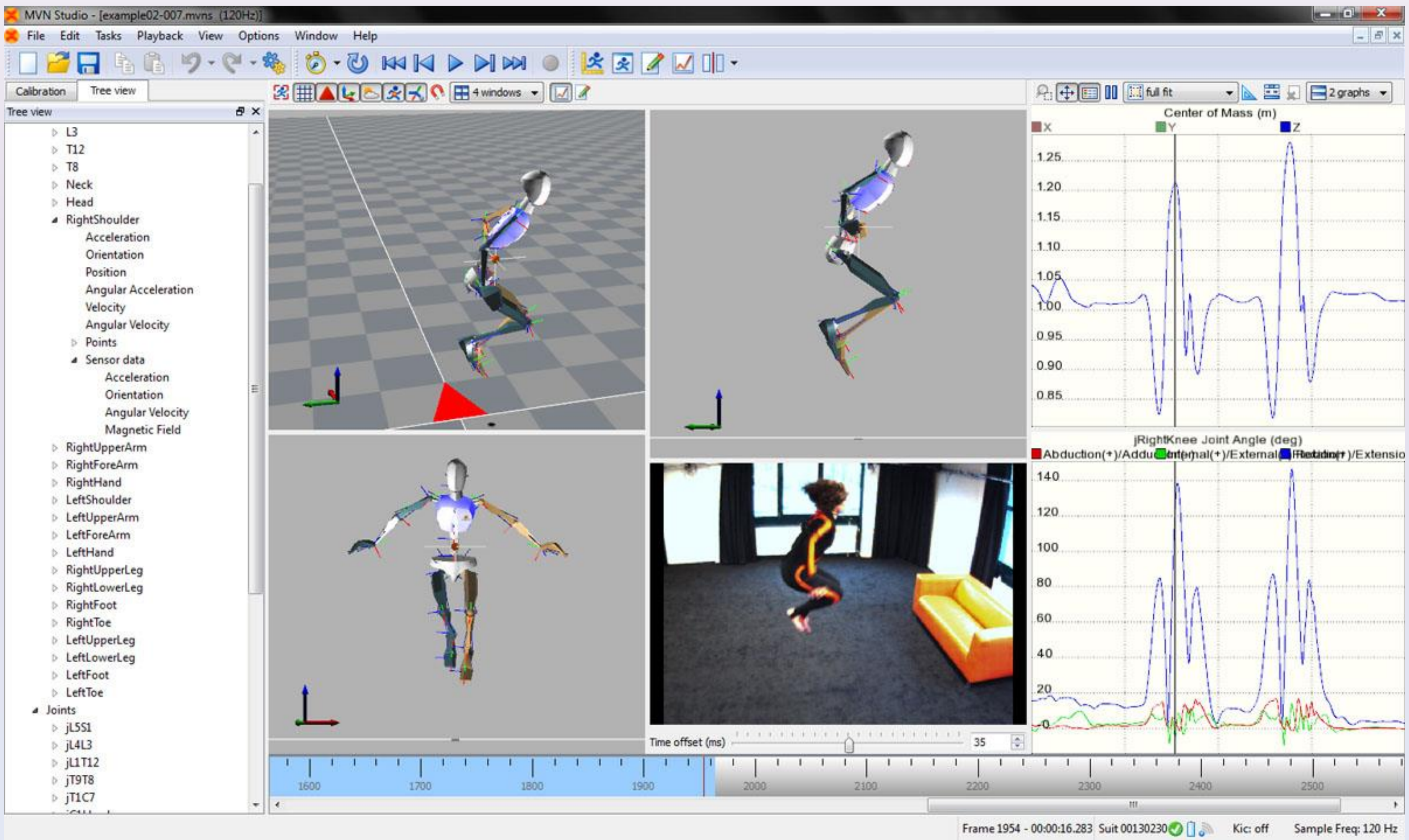


VICON. (OMG)
Plug-In-Gait

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

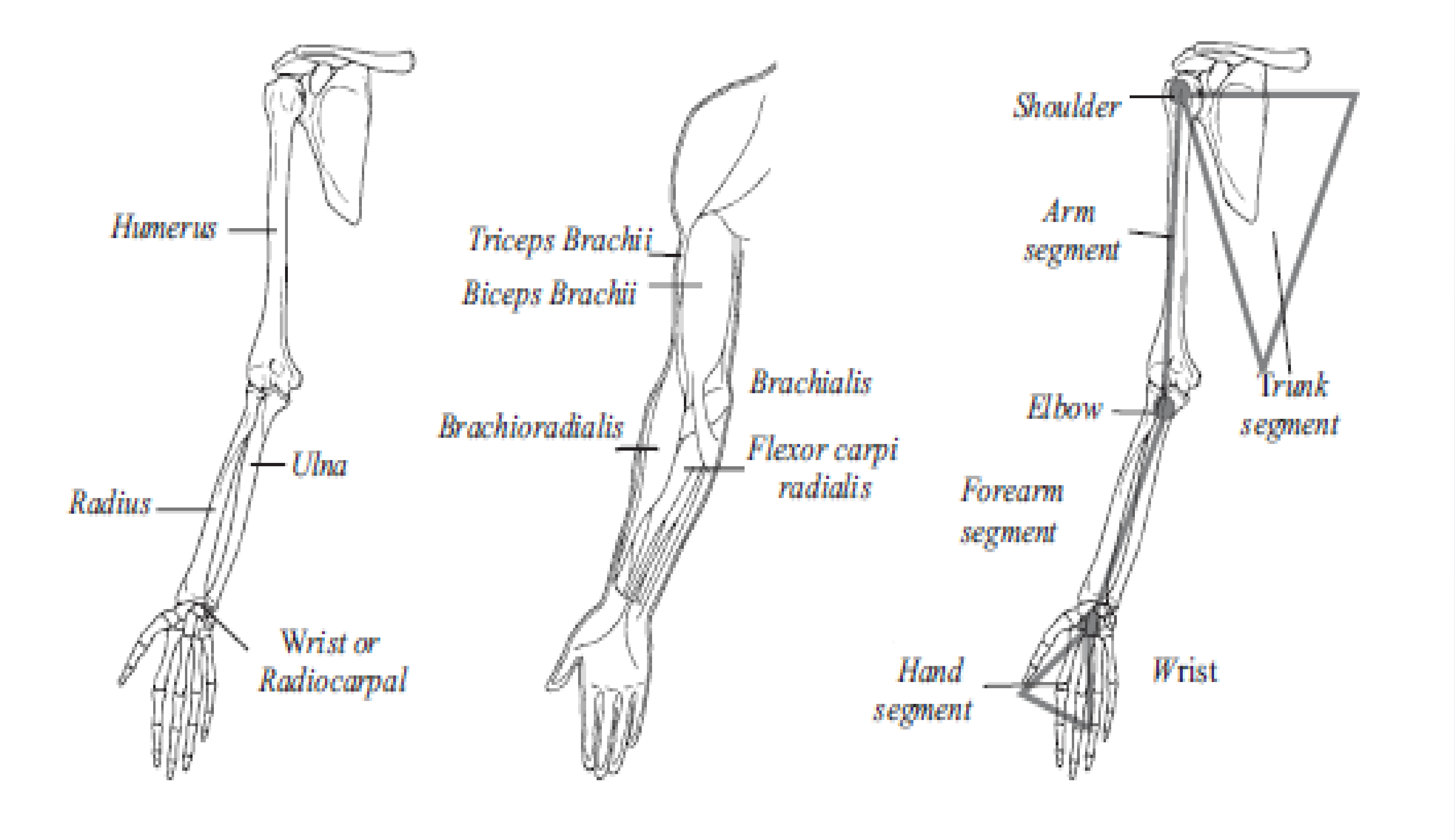
Movement description

- 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



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.

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 – 180º
    - extension: 30 – 80ª
- *Abduction – aduction*
  - *ROM*
    - *Abduction: 180 º*
    - *Adduction: 50º*
- *Rotation. (around humerus).*
  - *Internal Rotation (medial): 60-90º*
  - *External Rotation (lateral): 90º*
- The ROM for each DOF is large
- It can support the body weight

Elbow

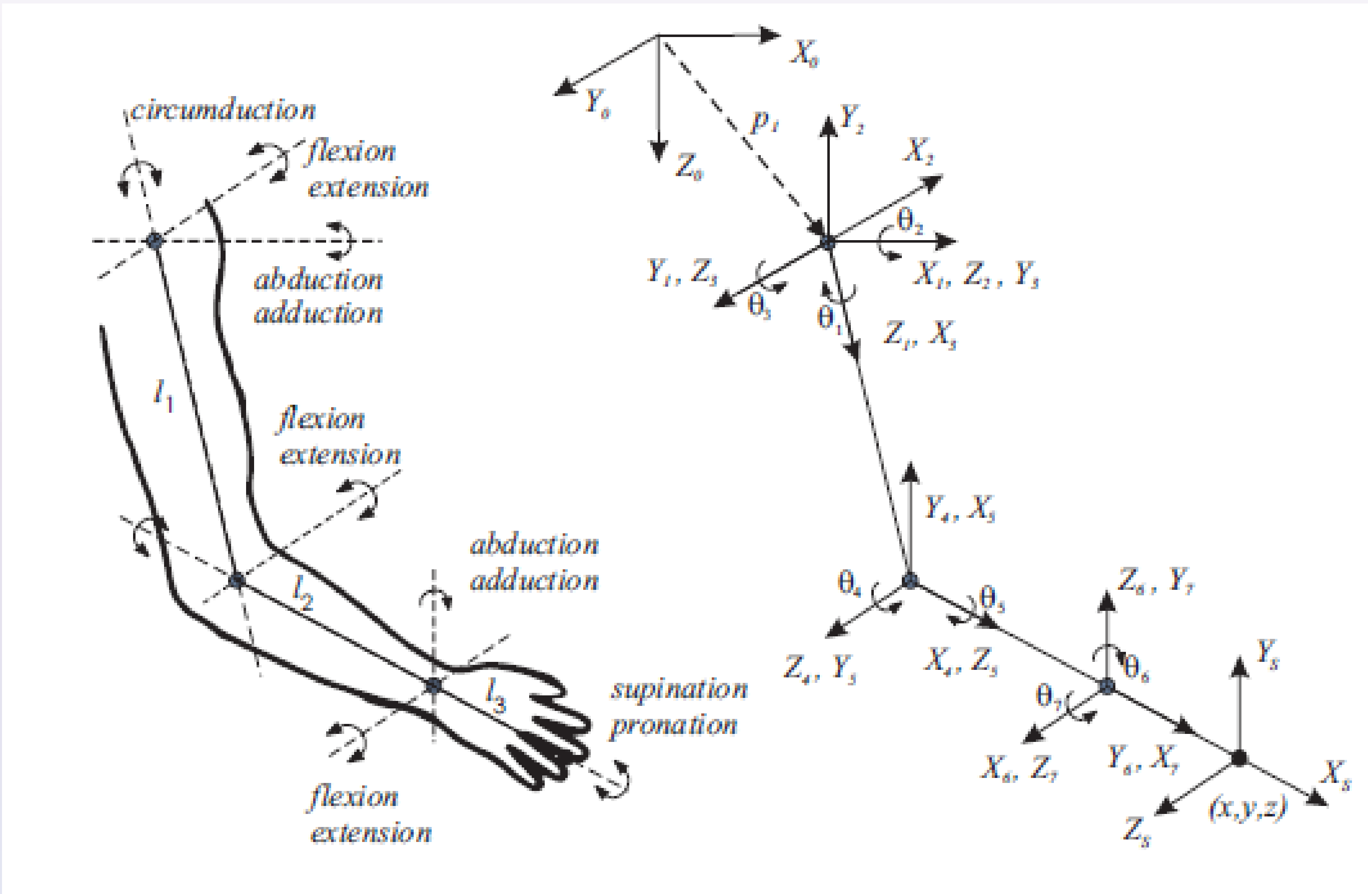
- Elbow. Arm-forearm joint.
- Three joints: humero-ulnar, humero-radial and radio-ulnar.
- Simplifiction: 2 DOF : *Flexion-extension. Pronation-supination*

- *Flexion-extension:*
  - *Funcionamento como articulação de dobradiça*
  - ROM de 0 a 140-146º
  - ROM atividades diarias; 30-130º
  - Consideração: eixo de Rotation é obliquo (inclinação lateral de 5 a 6 graus)

- *Pronation-supination.*
  - Definition from a 90º elbow flexion
  - *Pronation:* Max. 80º
  - *Supination:* Max 85º
  - 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: 90º
    - extension: 80º
  - Abduction- adduction:
    - Abduction: 15º
    - Aduction: 30-40º



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.

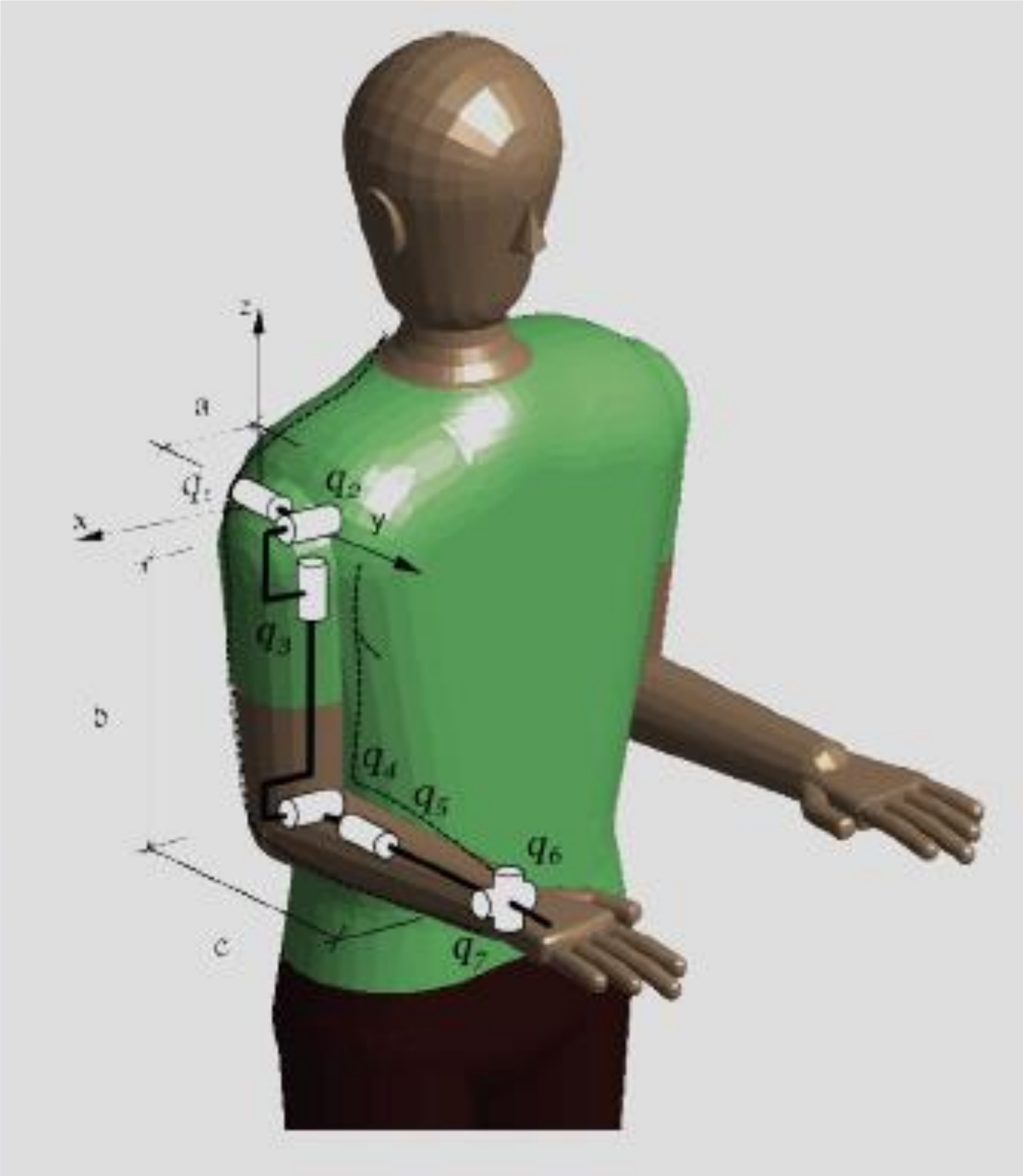
D-H parameters

Table 3.1 D–H parameters for arms segments.

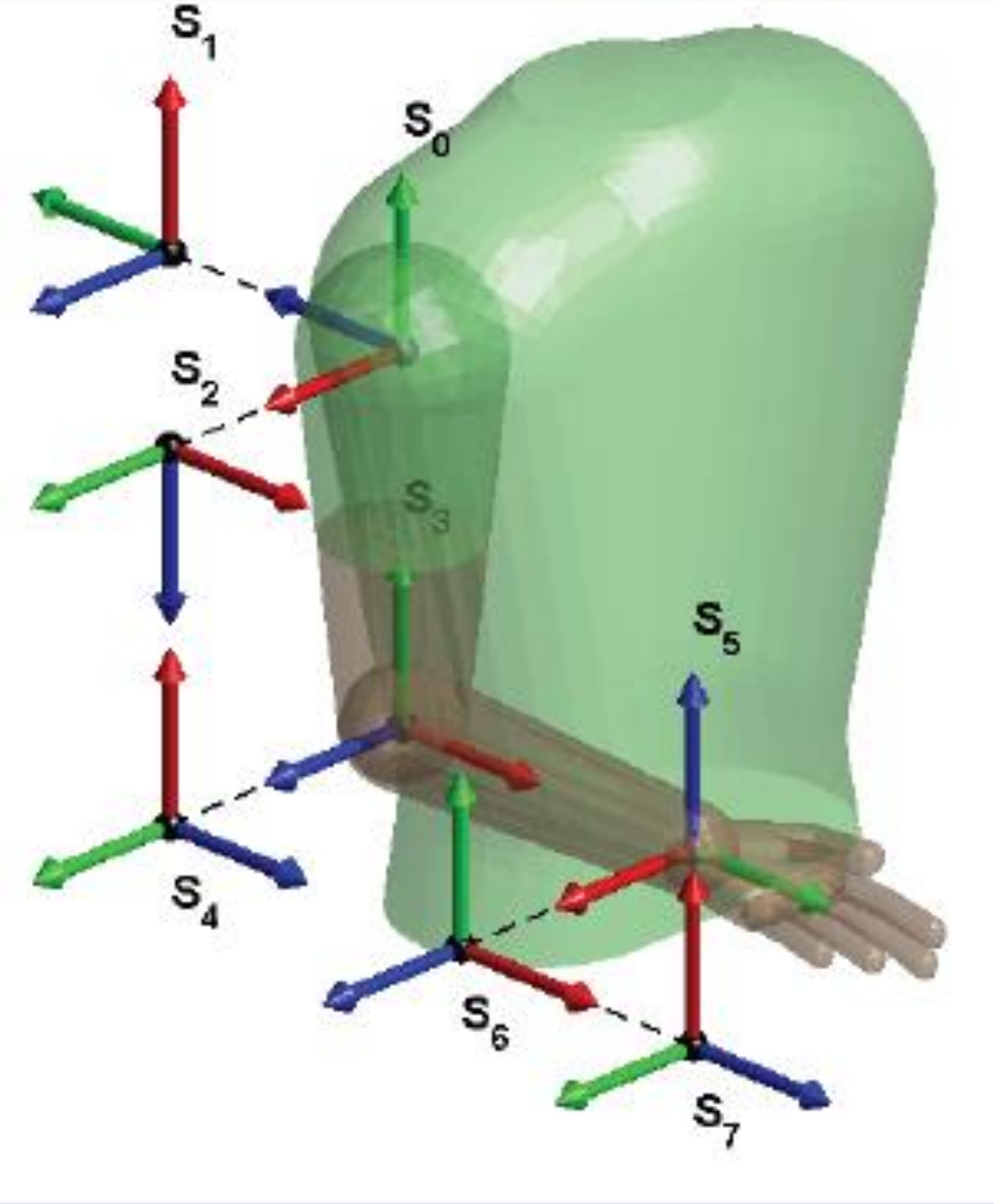
Joint	β_i	No.	α_i	a_i	d_i	θ_i
base	0	$1_{(0\longrightarrow 1)}$	0	a_0	d_0	0
shoulder	(-90) medial rot. / lateral rot. (+90)	$2_{(1\longrightarrow 2)}$	-90^o	0	0	$\beta_1 + 90^o$
shoulder	(-180) abduction / adduction (+50)	$3_{(2\longrightarrow 3)}$	$+90^o$	0	0	$\beta_2 + 90^o$
shoulder	(-180) flexion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

Anthropometrical data

Body segment	Lenght, 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

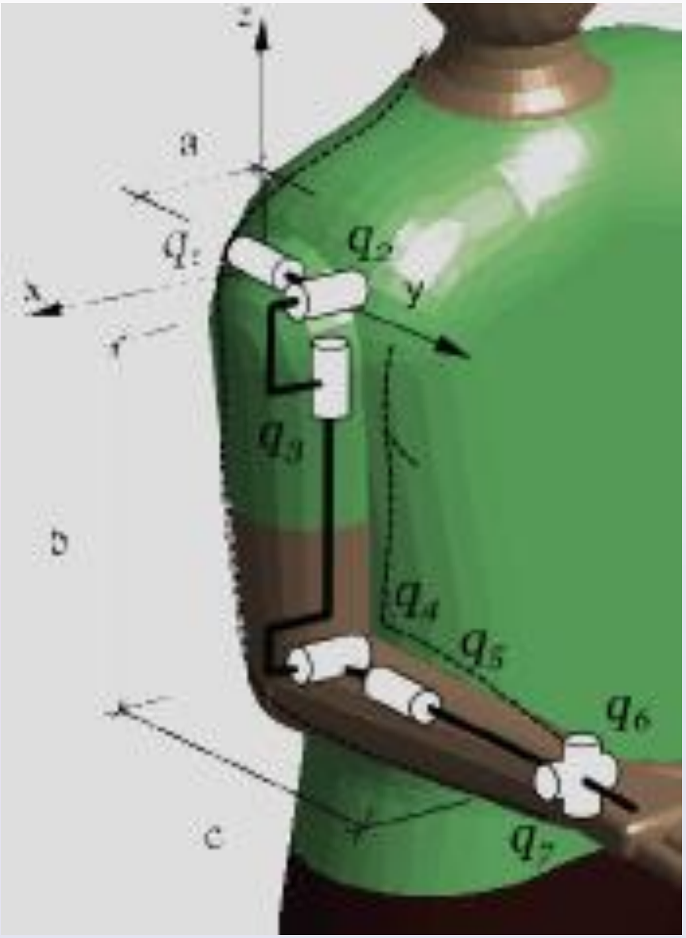


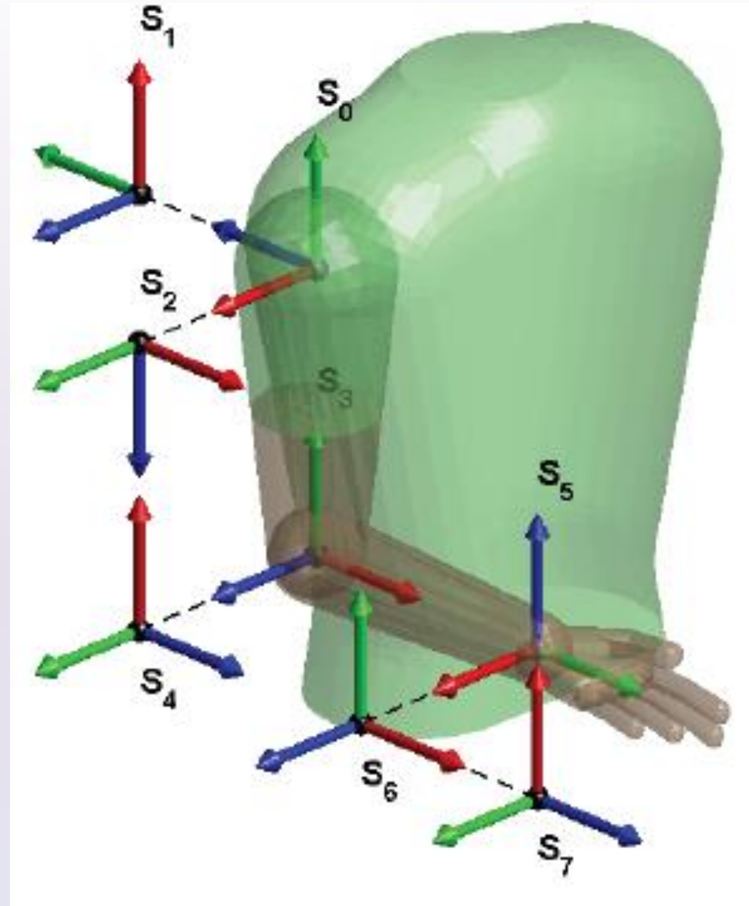
Bertomeu-Motos et al, 2015. EMBC

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	$\pi/2$

Bertomeu-Motos et al, 2015. EMBC

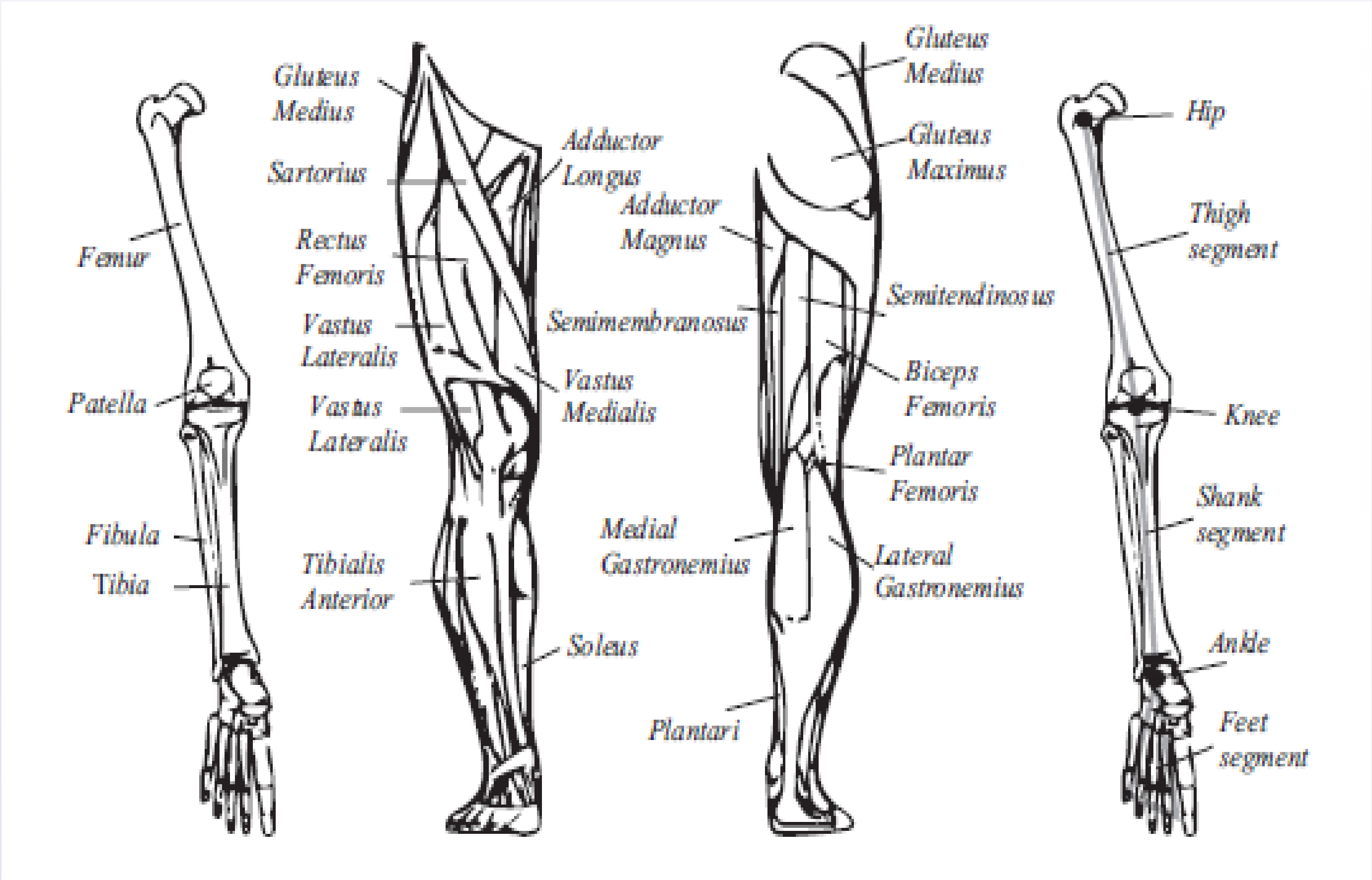




i	θ_i	d_i	a_i	α_i
1	$\pi/2 + q_1$	0	0	$\pi/2$
2	$3\pi/2 + q_2$	0	0	$\pi/2$
3	q_3	l_u	0	$-\pi/2$
4	$\pi/2 + q_4$	0	0	$\pi/2$

Bertomeu-Motos et al, 2015. EMBC

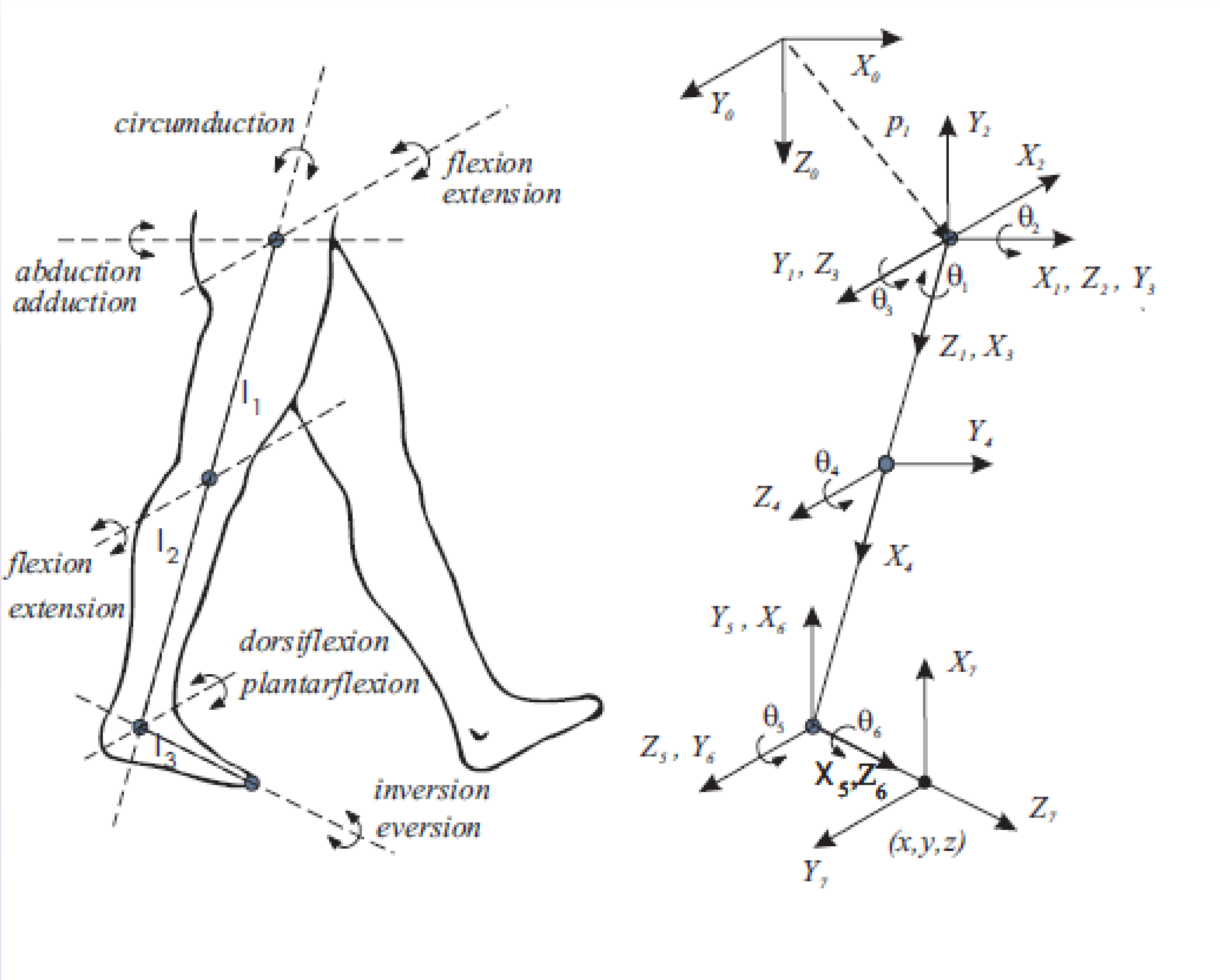
Leg anatomy



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.

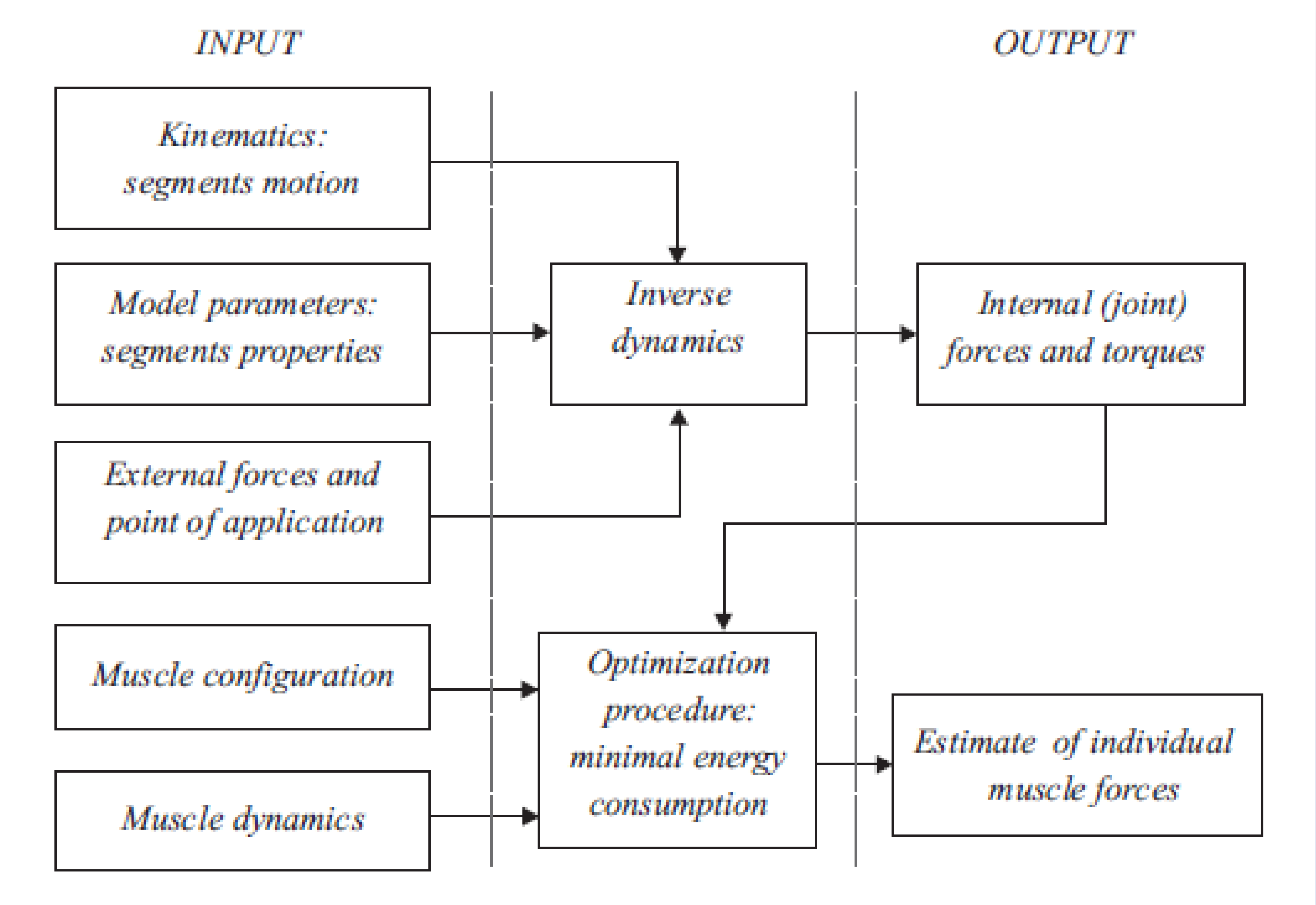
Membro inferior

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



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.

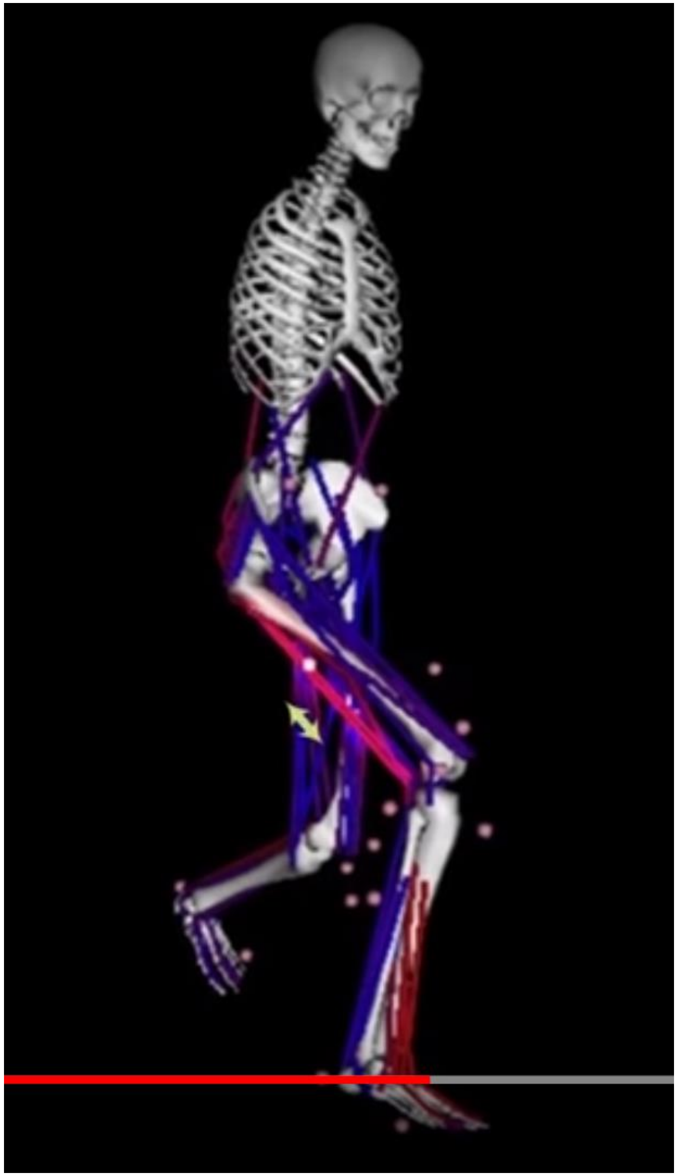
5. Direct and inverse dynamics



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

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.

OpenSim



- Thank you for your attention

Project definition

Example