A comparative assessment of performance of active exoskeletons for haptic feedback: tendon driven vs harmonic drive based designs

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HS' 2012
Workshop on Hardware Evaluation

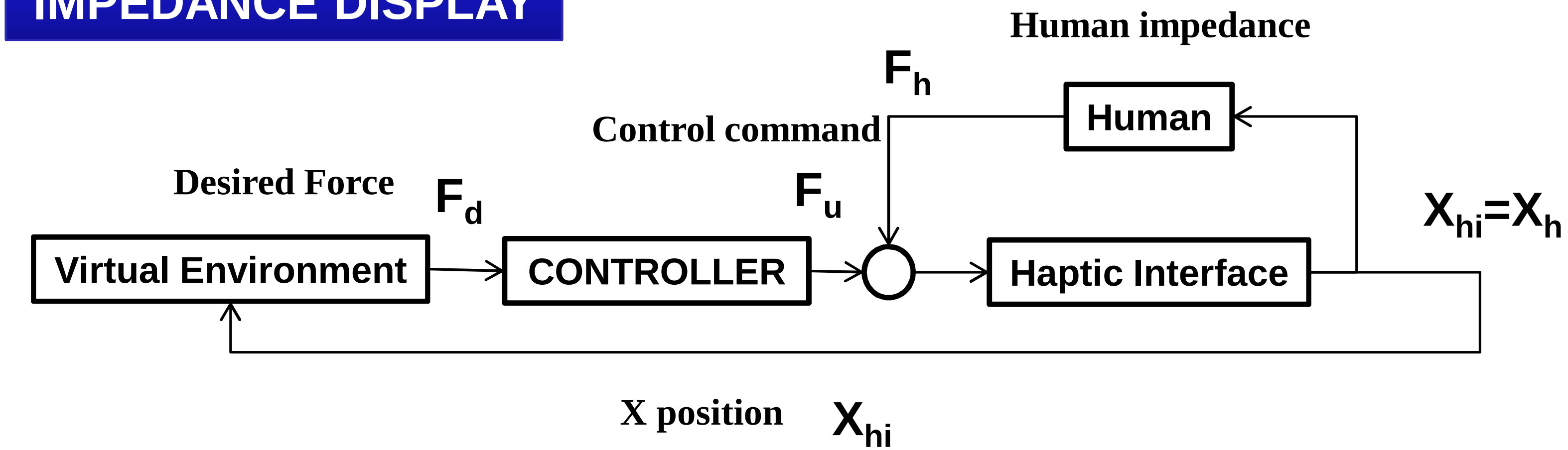
Wearable devices development - exoskeletons

- The rationale for the design of high performance haptic interface are the satisfaction of the requirements of
  - high force fidelity
  - transparency
  - backdrivability.
- It is well known that two main basic approaches can be adopted in the design of haptic interfaces and more specifically of active exoskeletons:
  - impedance based design
  - admittance based design

ZURICH

Admittance vs. impedance display

IMPEDANCE DISPLAY



Human impedance

F_h

Human

Control command

Desired Force

F_d

F_u

$X_{hi}=X_h$

Virtual Environment

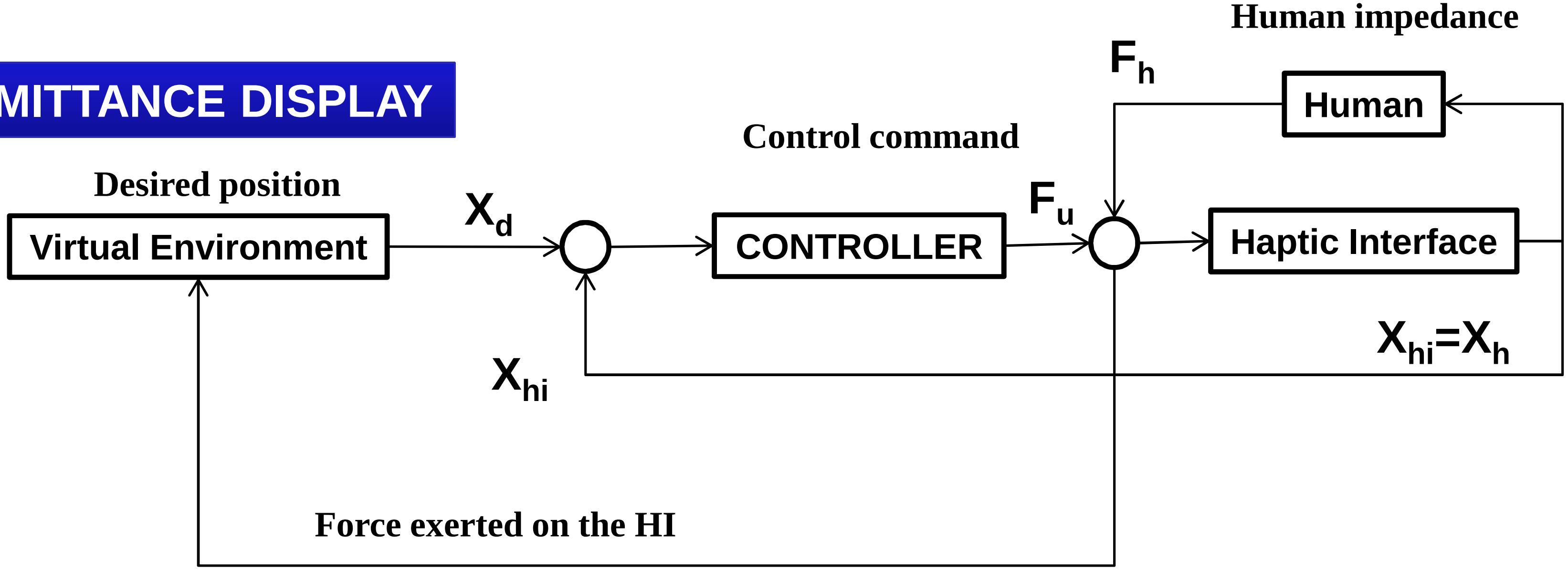
CONTROLLER

Haptic Interface

X position

X_{hi}

ADMITTANCE DISPLAY



Human impedance

F_h

Human

Control command

Desired position

X_d

F_u

Virtual Environment

CONTROLLER

Haptic Interface

$X_{hi}=X_h$

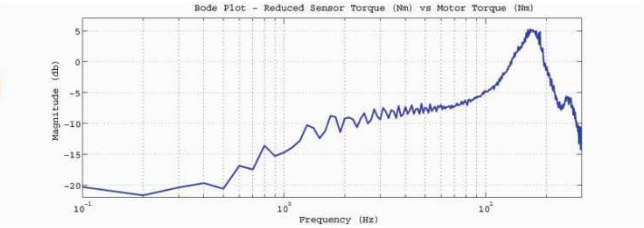
X_{hi}

Force exerted on the HI

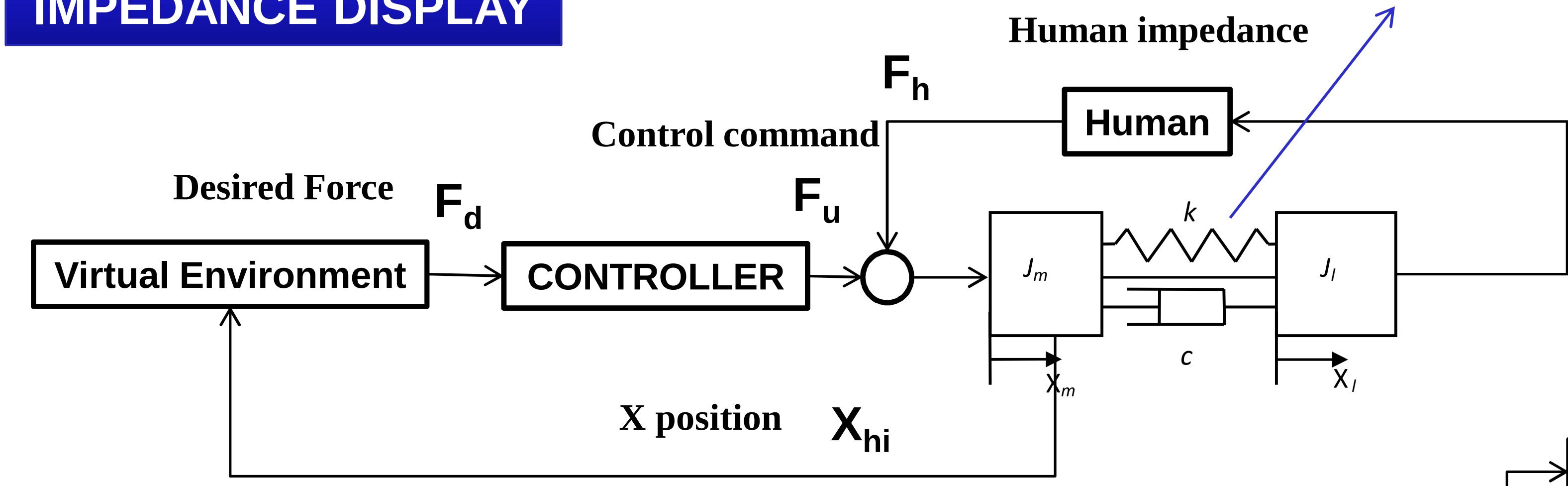
ISTITUTO DI TECNOLOGIE DELLA COMUNICAZIONE, DELL'INFORMAZIONE E DELLA PERCEZIONE

Scuola Superiore Sant'Anna

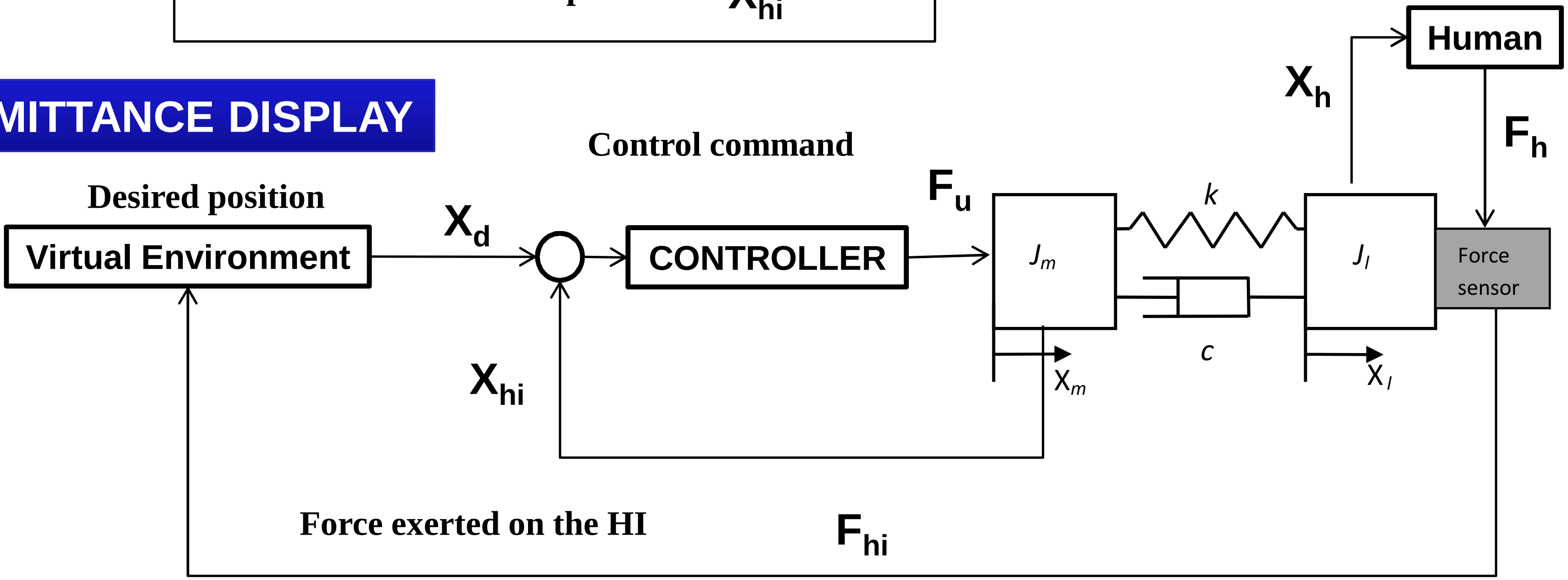
Admittance vs. impedance display



IMPEDANCE DISPLAY



ADMITTANCE DISPLAY



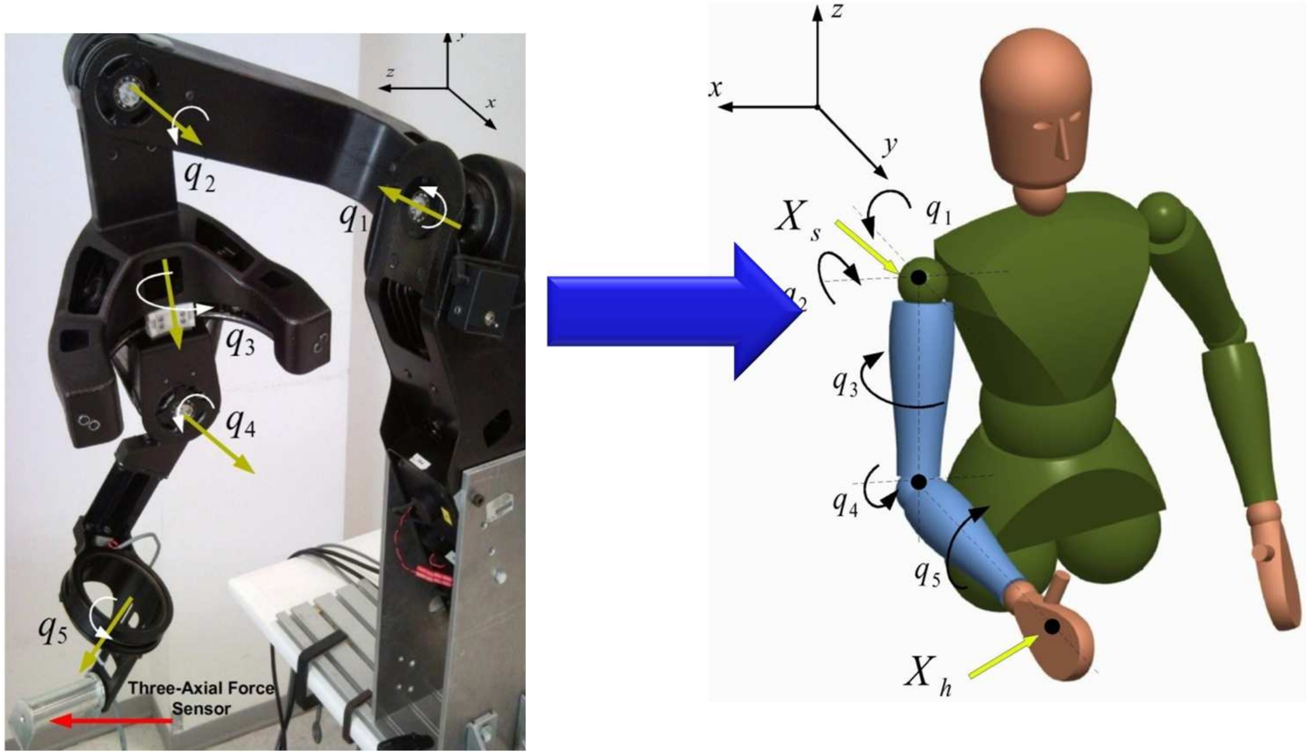
Human impedance

A tendon driven exoskeleton

THE L-EXOS SYSTEM

Antonio Frisoli, Caterina Procopio, Carmelo Chisari, Ilaria Creatini, Luca Bonfiglio, Massimo Bergamasco, Bruno Rossi, Maria Chiara Carboncini,"Positive effects of robotic exoskeleton training of upper limb reaching movements after stroke", accettato per la pubblicazione, in stampa in Journal of Neuroengineering and Rehabilitation (IF 2.638) (May 2012)

System overview



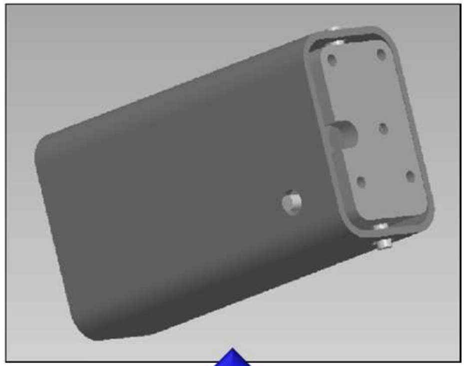
The basic movements of the human arm are controlled for all time, attenuating undesired excessive motions of each human arm movement, i.e., abduction/adduction, flexion/extension,internal/external rotation and pronation/ supination

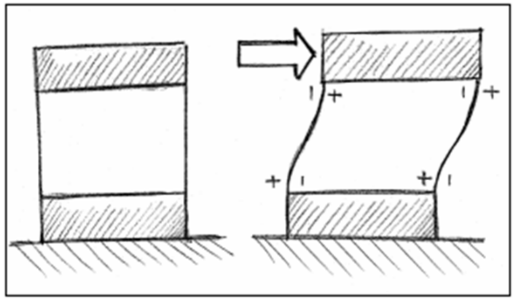
- L-exos is characterized by a serial kinematics consisting of five rotational joints.
- The first three rotational axes are incident and mutually orthogonal (two by two) in order to emulate the kinematics of a spherical joint with the same center of rotation of the human shoulder.
- Handle is sensorized with a custom design force sensor

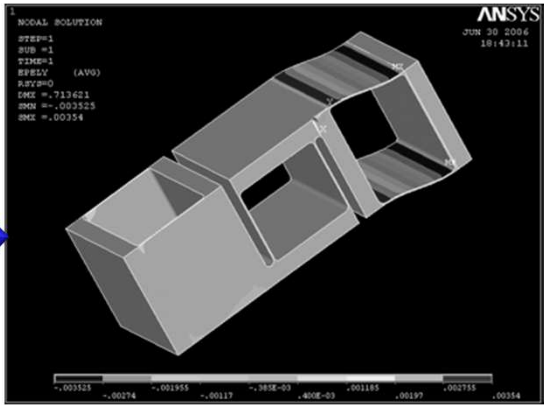
Frisoli, A. Montagner, L.i Borelli, F. Salsedo, M. Bergamasco, "A force-feedback exoskeleton for upper limb rehabilitation in Virtual Reality", Applied Bionics and Biomechanics 6(2), pp115-126, (2009)

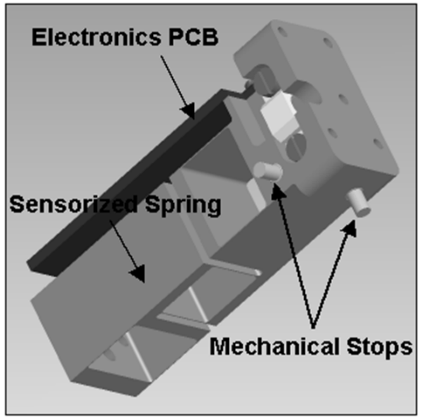
EF forse sensing

- -Three Axial Force Sensor.
  - -Maximum Load: 100 N.
  - -Resolution 0.0500 Volts/N.
  - -Three axial sensing.
  - -Nonlinearity 3%.
  - -Made in PERCRO.



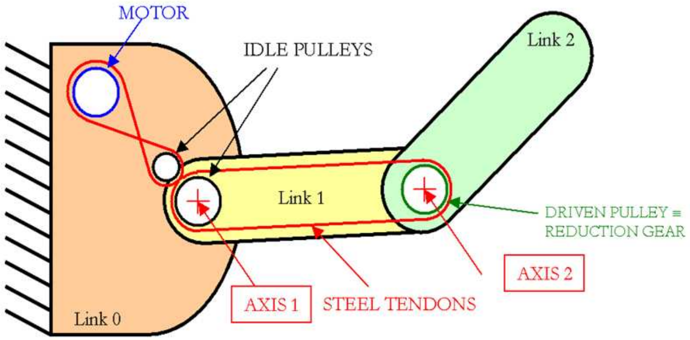


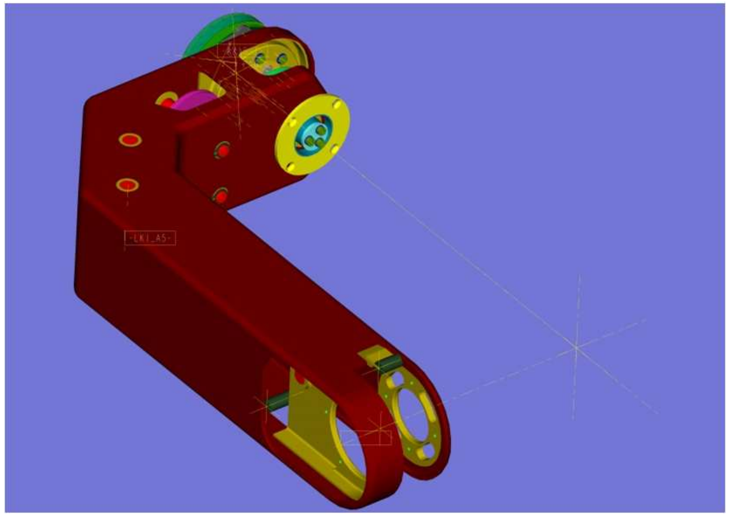




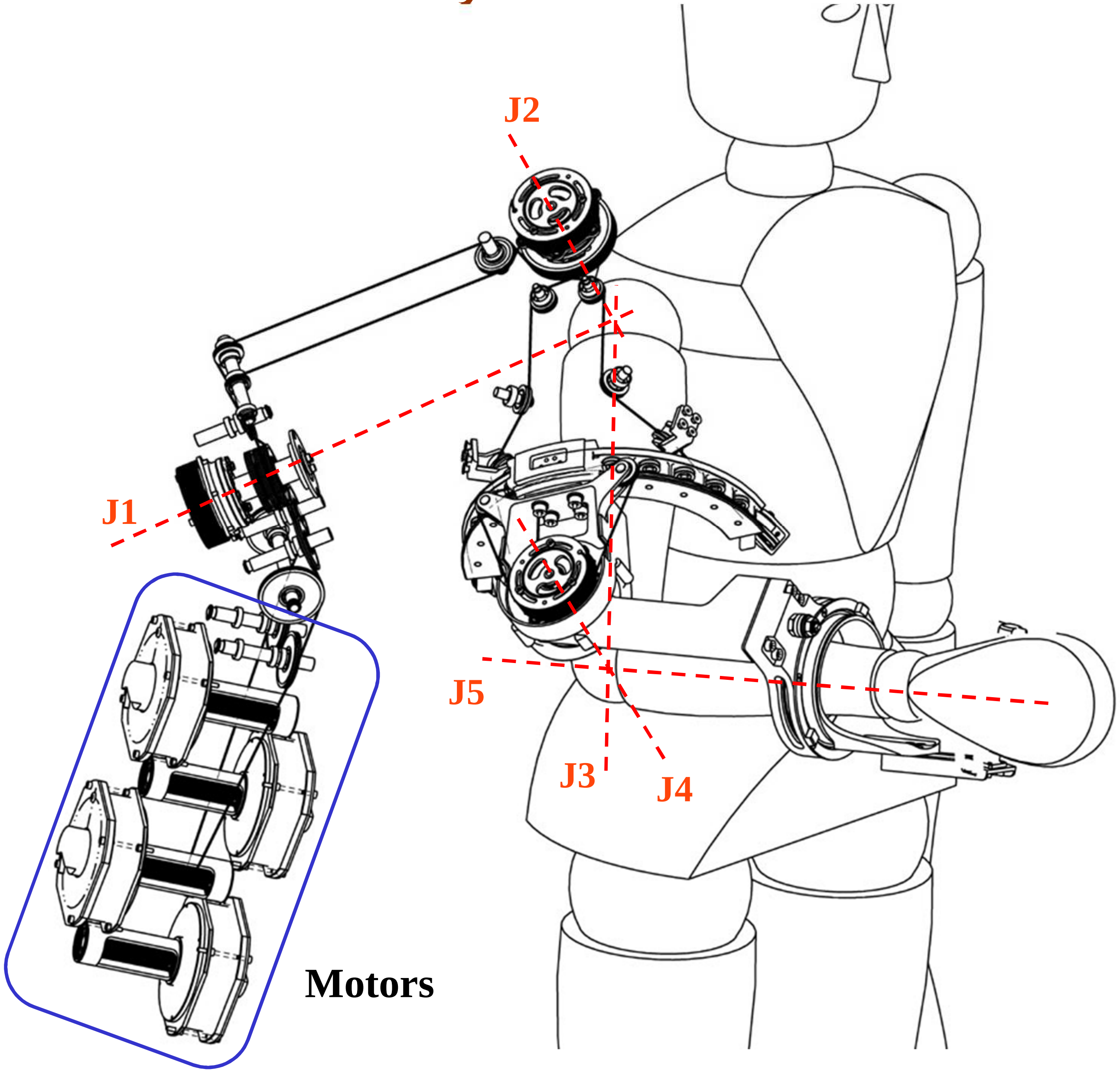
Mechanical Constructive Features

All the motors located on Link 0	**Reduction of the masses of the moving parts near 40%**
Reduction gear integrated at the joint axis	**Increase of stiffness at the end effector**
	Reduction of mass of transmission systems and of the structural parts
Structural components designed as thin-wall parts (mechanical parts integrated within the links)	**Increase of stiffness at the end effector**
	Improvement of protection for inner parts
	Increase of protection for user from potential harm deriving
Structural components made of carbon fiber	**Further Improvement of lightness and stiffness**

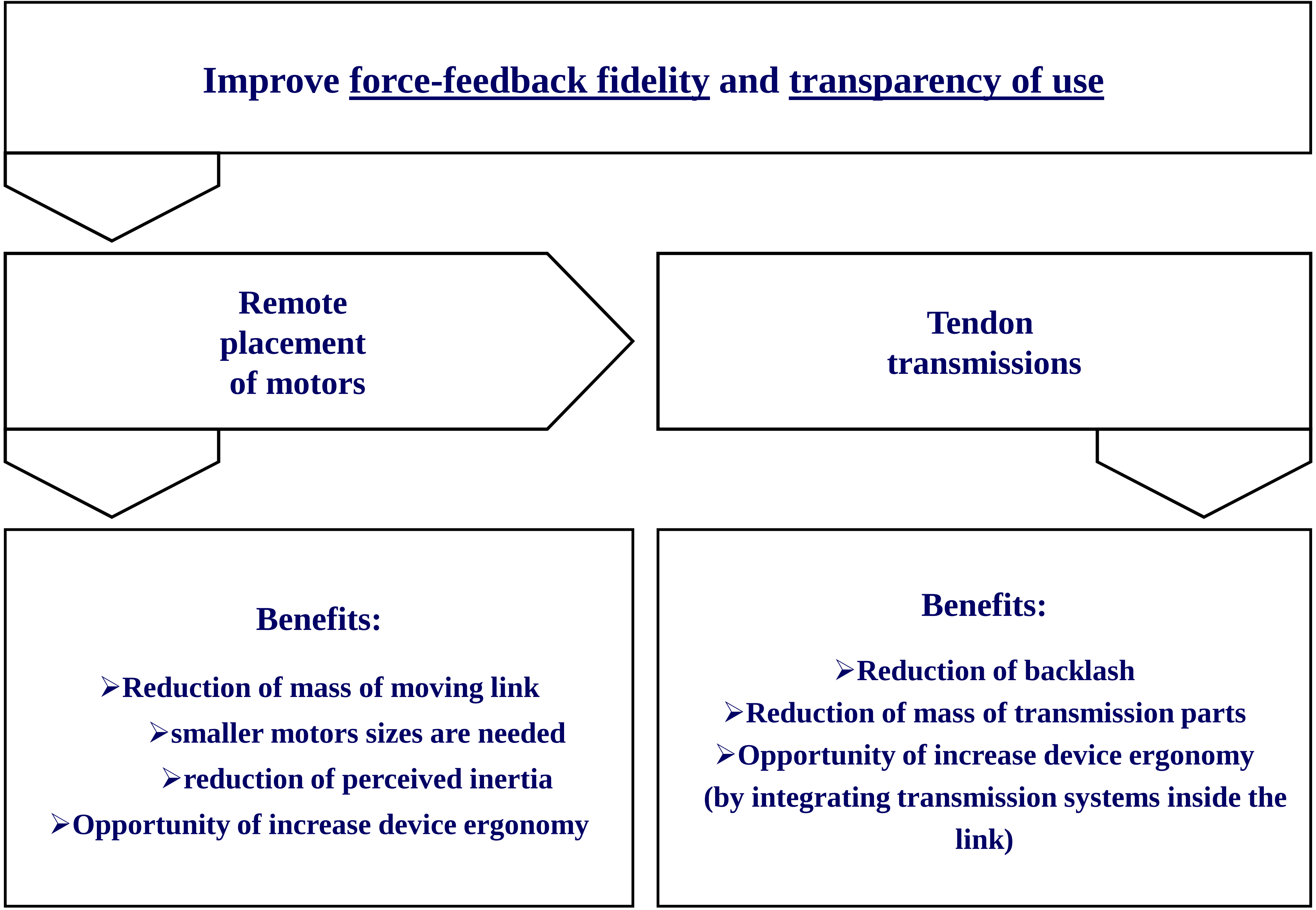




Exos transmission system



Why complex tendon transmission



Improve force-feedback fidelity and transparency of use

Remote placement of motors

Tendon transmissions

Benefits:

- ➢Reduction of mass of moving link
  - ➢smaller motors sizes are needed
  - ➢reduction of perceived inertia
- ➢Opportunity of increase device ergonomy

Benefits:

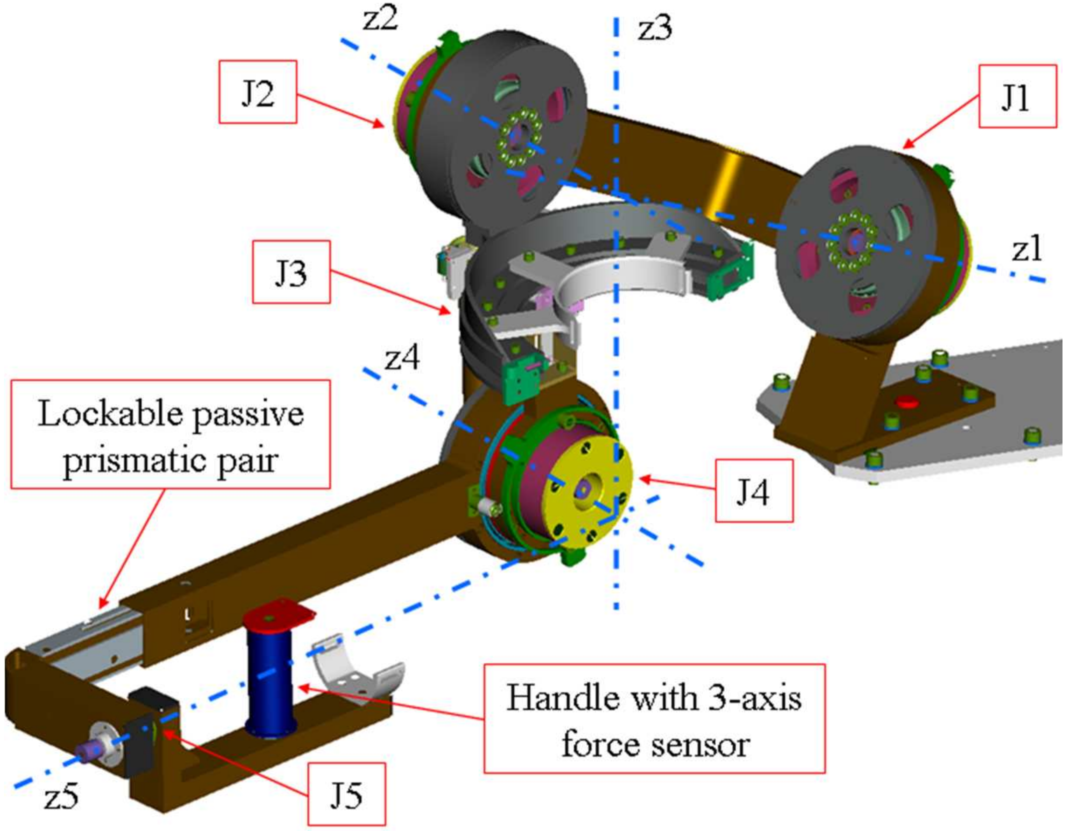
- ➢Reduction of backlash
- ➢Reduction of mass of transmission parts
- ➢Opportunity of increase device ergonomy (by integrating transmission systems inside the link)

THE REHAB-EXOS SYSTEM

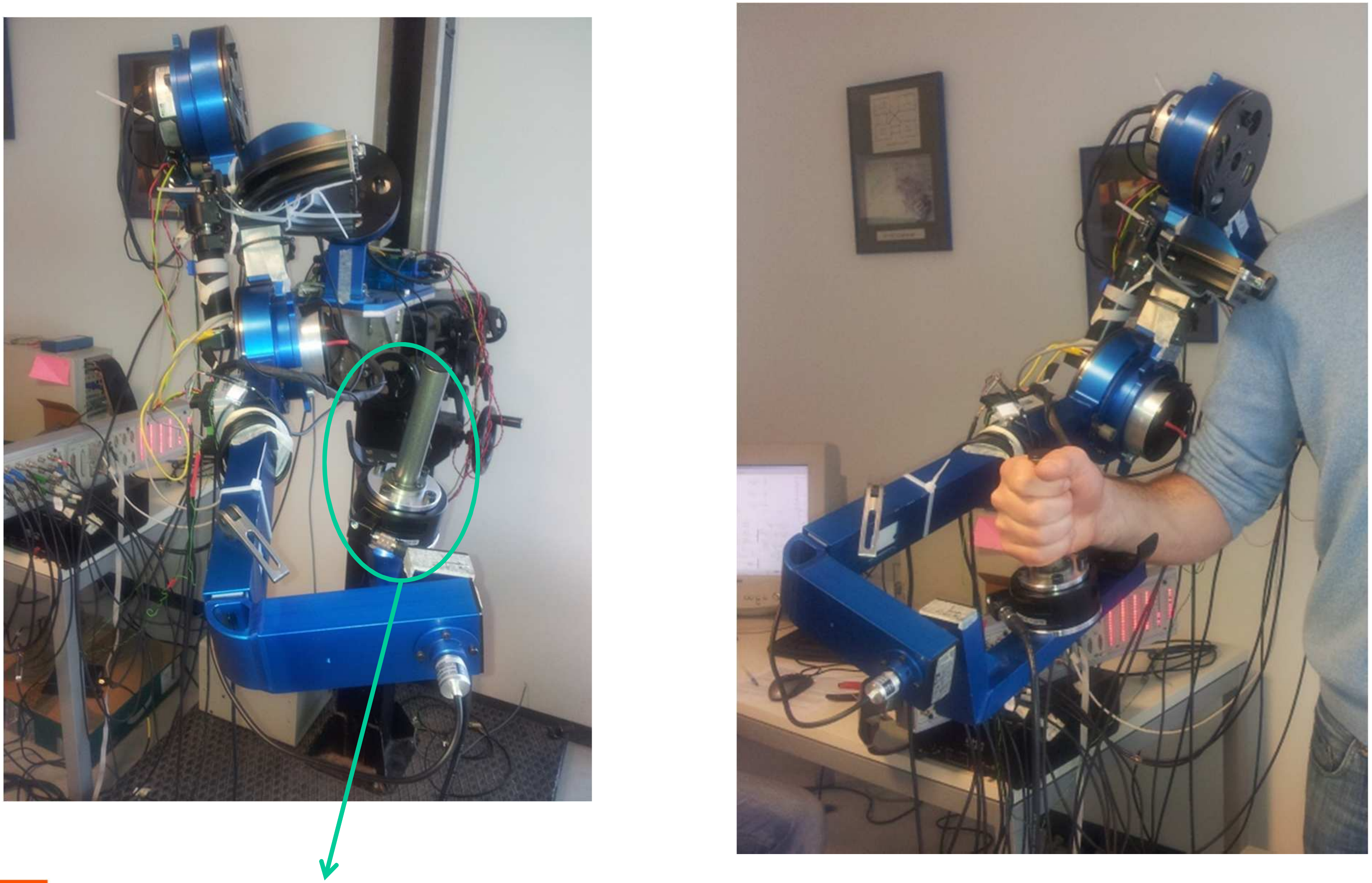
New Exoskeleton for Upper-Limb Rehabilitation

A new exoskeleton has been developed which features:

- **Isomorphism with the human arm kinematics;**
- **4 actuated DOFs;**
- **1 passive DOF;**
- **Handle with 3-axis force sensor;**
- **In-loco actuation;**
- **Modular design based on custom made robotic joints;**
- **Joint torque sensors.**



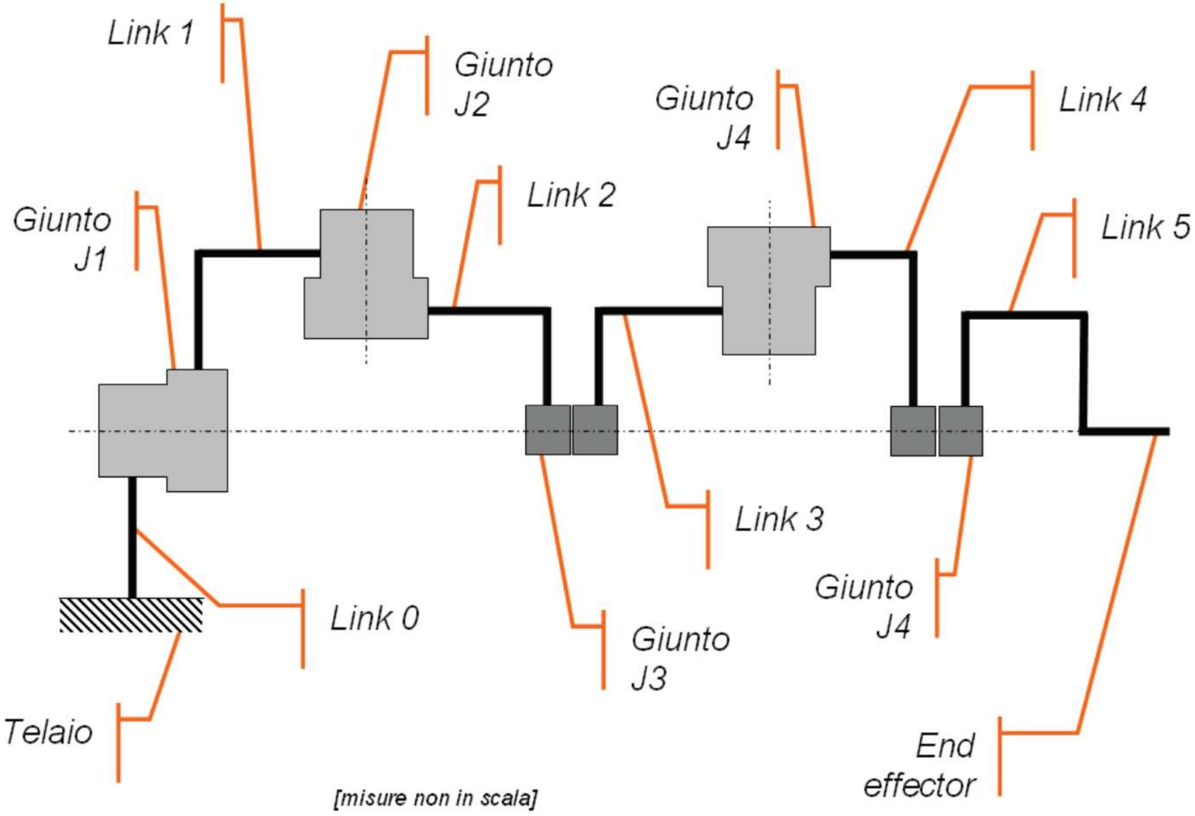
Vertechy, R.; Frisoli, A.; Dettori, A.; Solazzi, M.; Bergamasco, M.; , "Development of a new exoskeleton for upper limb rehabilitation,"Rehabilitation Robotics, 2009. ICORR 2009. IEEE International Conference on, vol., no., pp.188-193, 23-26 June (2009)



ATI force sensor at the handle to monitor forces

Overall architecture of the Rehab-Exos

- The design is based on 4 actuated joints and 5 dofs.



Frisoli et al. , ICORR, Kyoto 23-26, June 2009

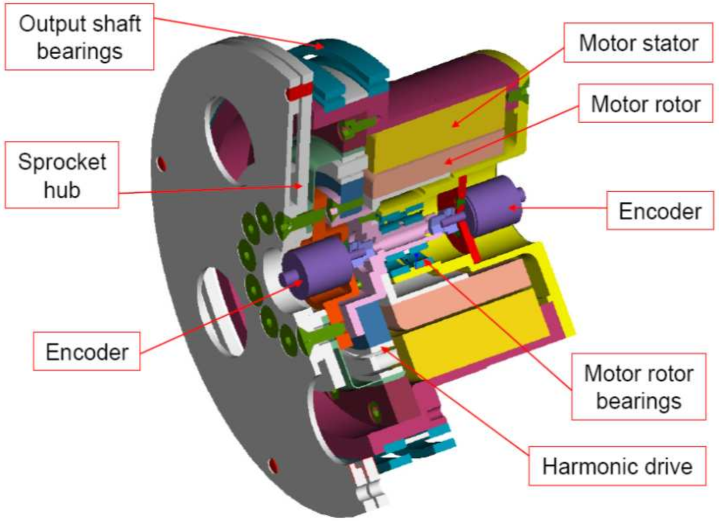
New Robotic Joints for Rehabilitation Exoskeletons

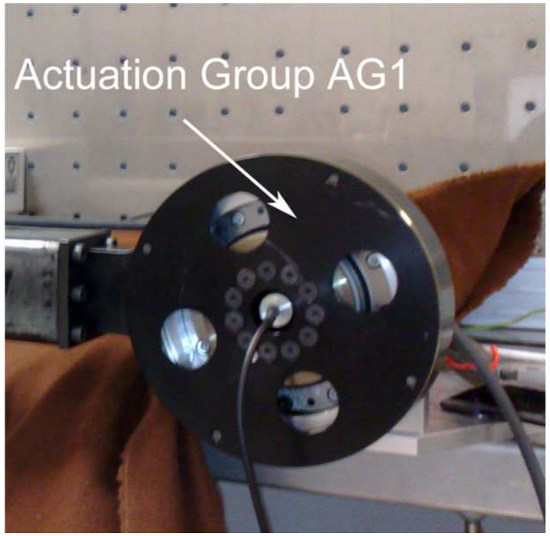
Novel custom made Robotic joints featuring:

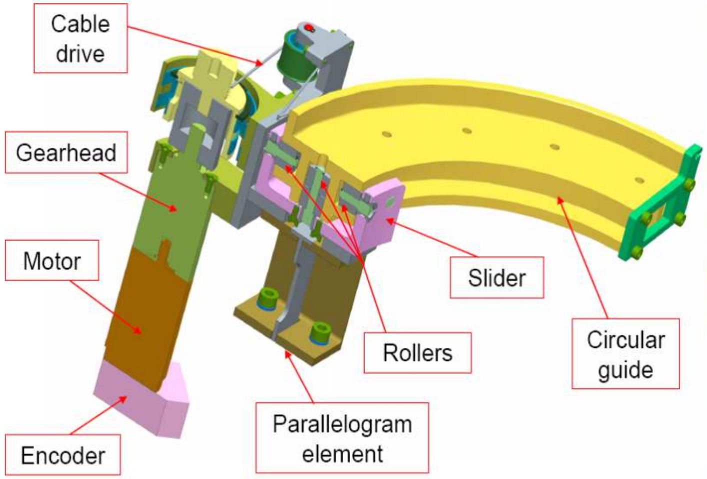
- **Electric motors;**
- **Transmissions with large reduction ratio;**
- **Position sensors;**
- **Integrated joint torque sensors;**
- **Inherent passive compliance.**

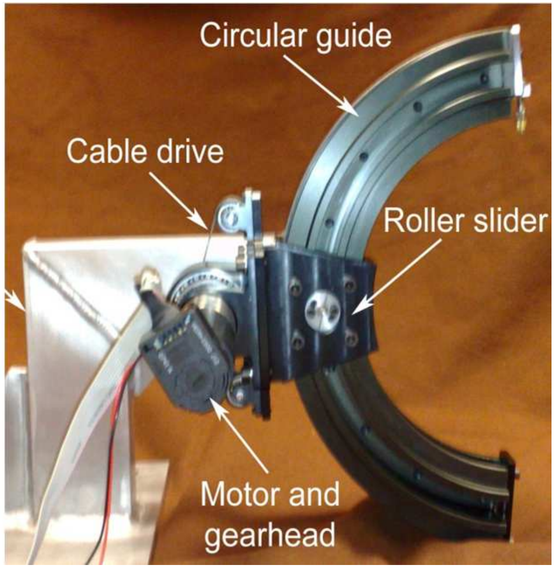
Joint performances:

- **10rpm max. output velocity;**
- **120Nm nominal maximum output torque;**
- **Reduced weight (3.7Kg and 2.2Kg);**
- **Torque sensor accuracy by 0.5% of full scale (120Nm).**

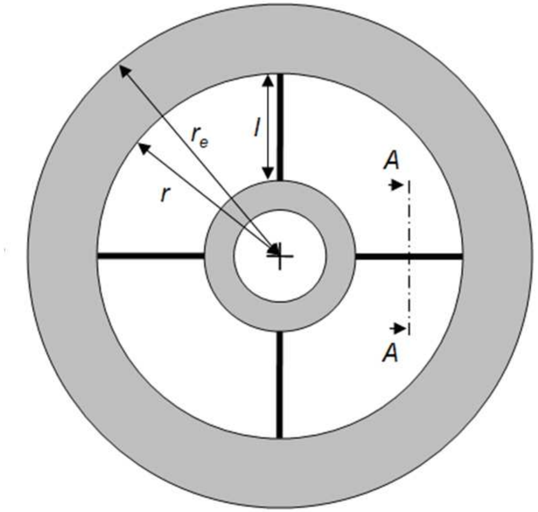


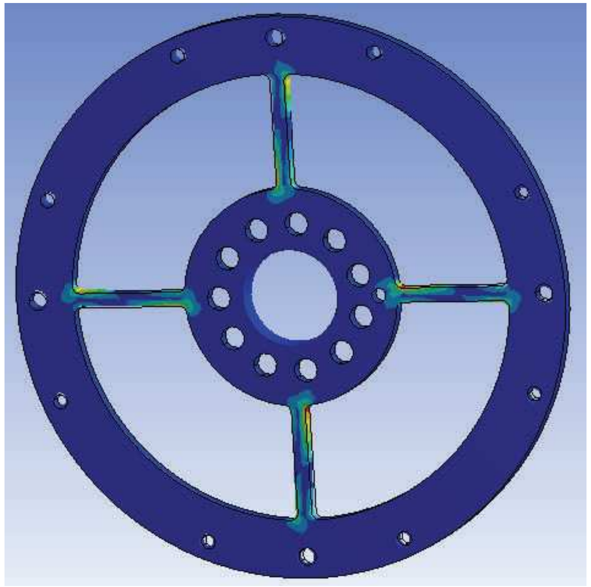






Force sensor design

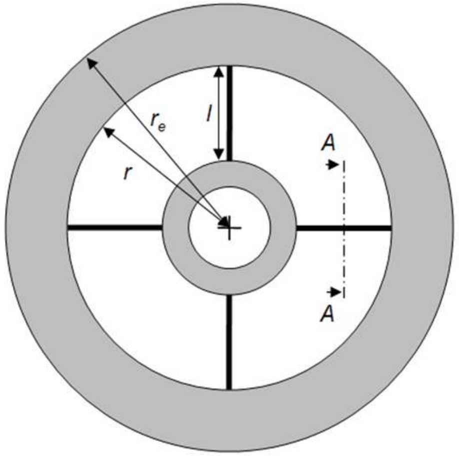


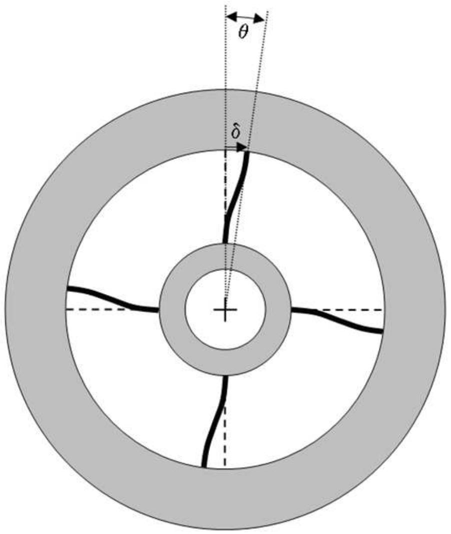


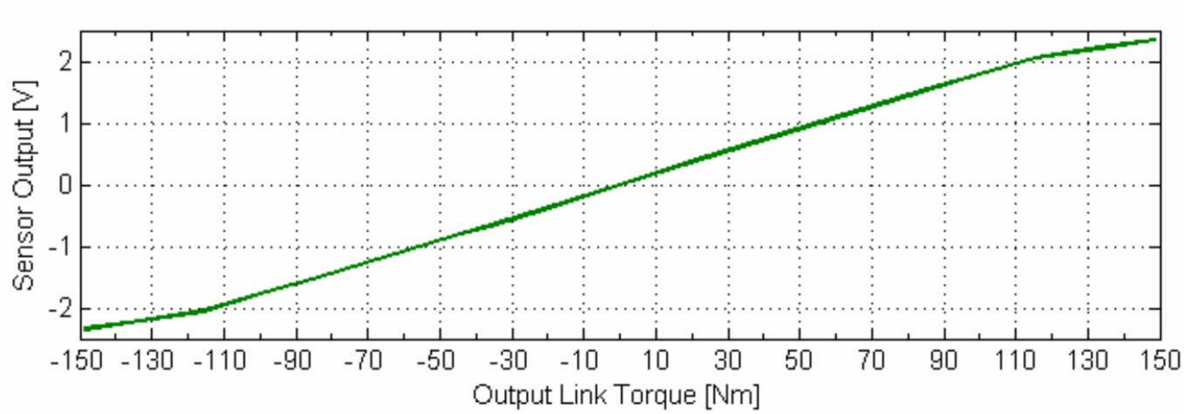
- **The employed force sensor has a cross geometry.**
- **All structure loads are supported by the joint, while only the motor torque is transmitted through the sensor.**

Frisoli et al. , ICORR, Kyoto 23-26, June 2009

Force sensor design





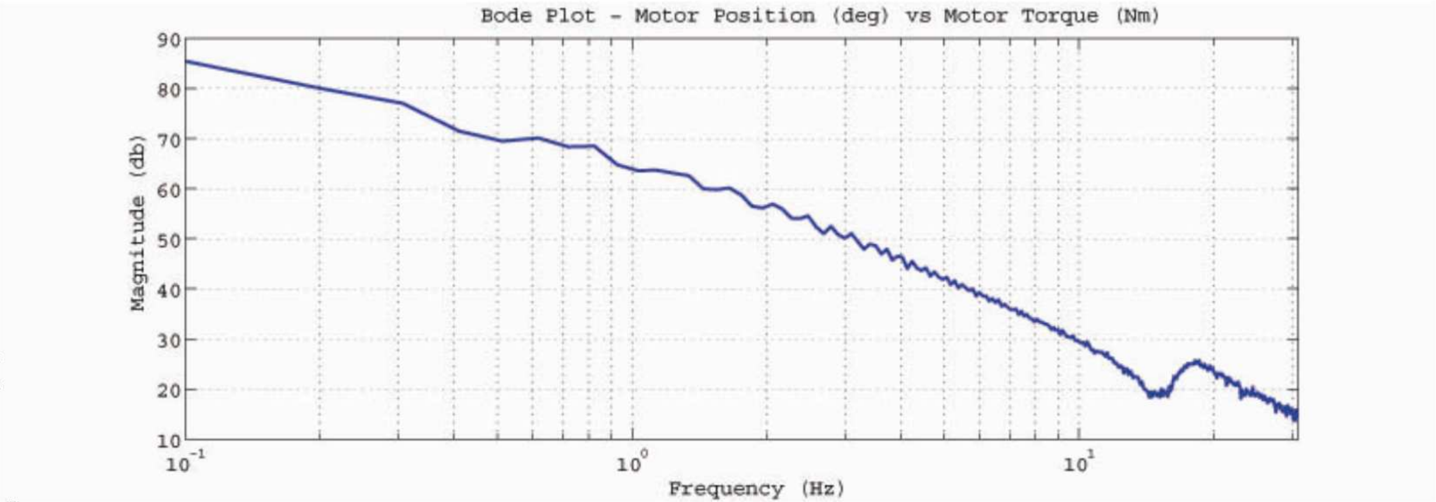


- **In the operating range, the sensor presents almost a linear operating curve**

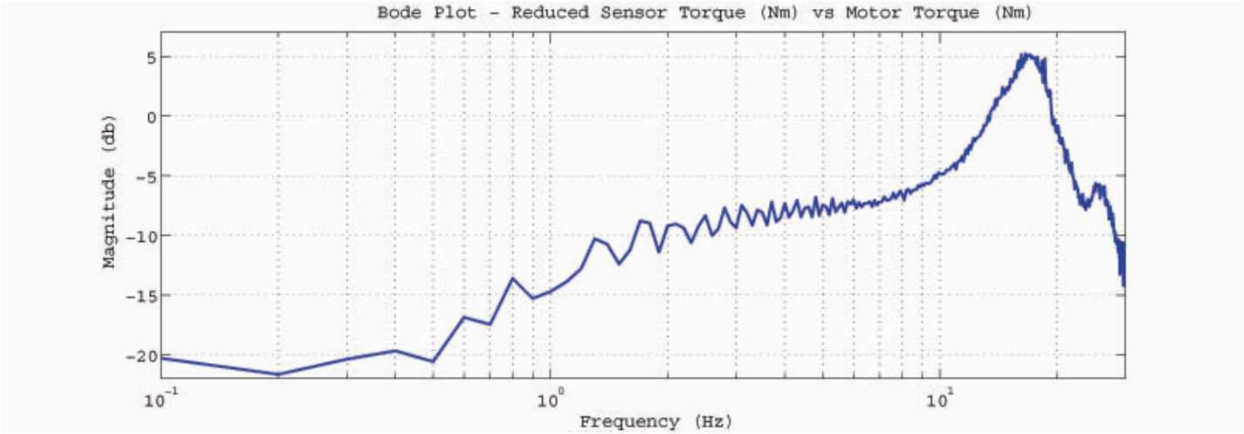
Frisoli et al. , ICORR, Kyoto 23-26, June 2009

Dynamic experimental characterization

- The system presents a dynamic bandwidth o 18Hz, as it c seen by the experimental Bode diagrams obtained.



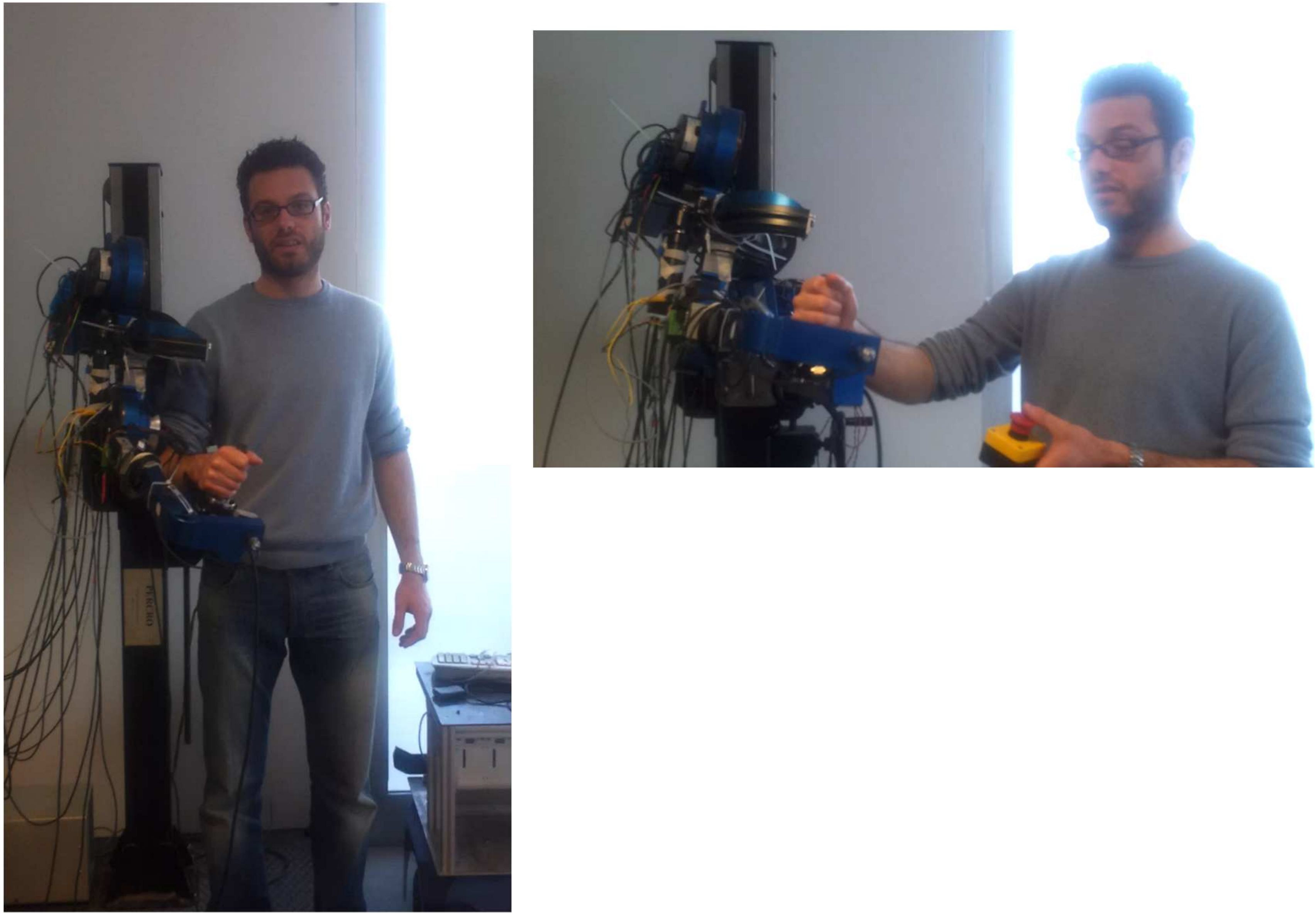
Frequency response



Force response

Frisoli et al. , ICORR, Kyoto 23-26, June 2009

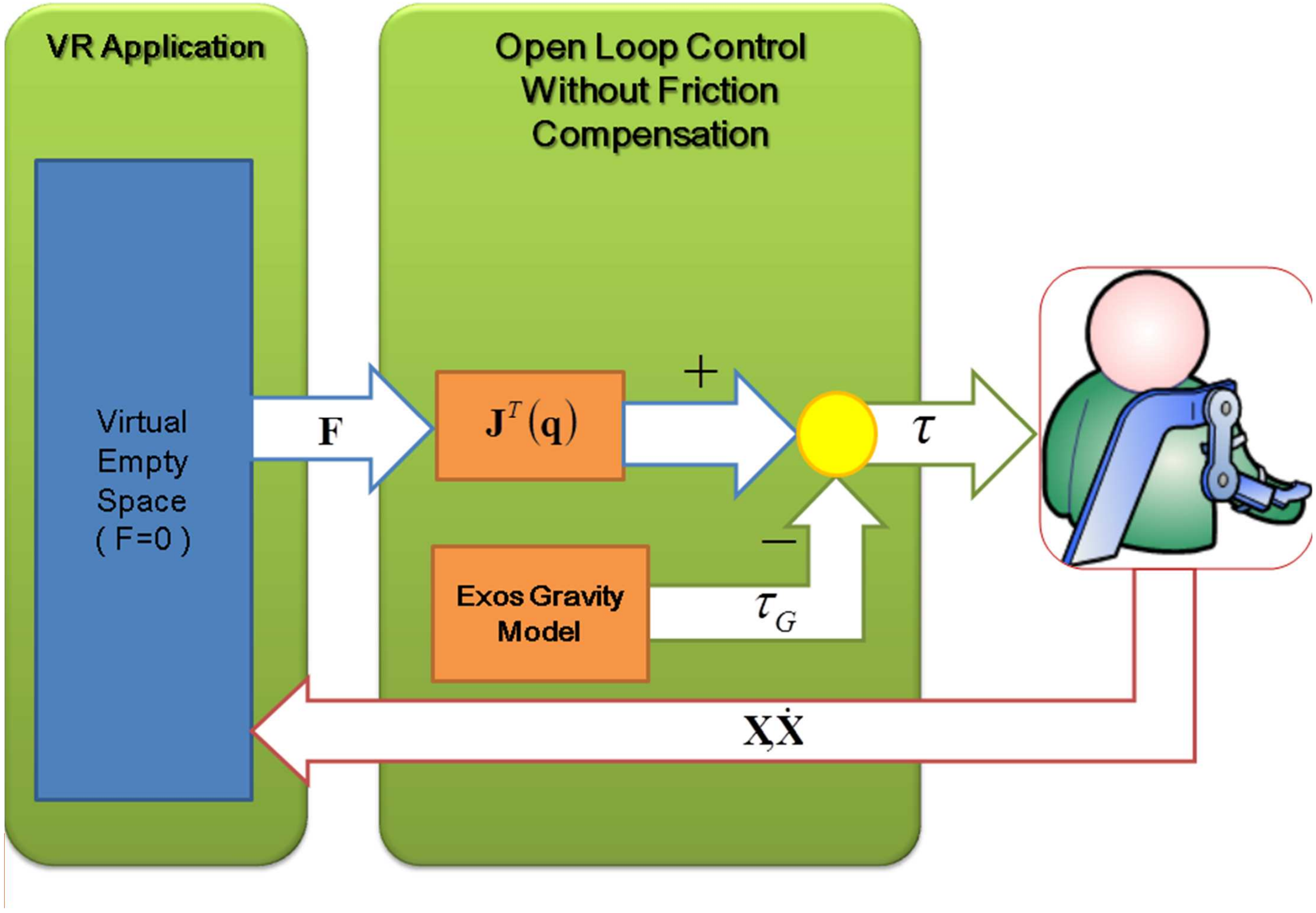
System backdrivable by control



PRINCIPLES OF CONTROL DESIGN AND PERFORMANCE EVALUATION

A tendon driven exoskeleton

THE L-EXOS SYSTEM

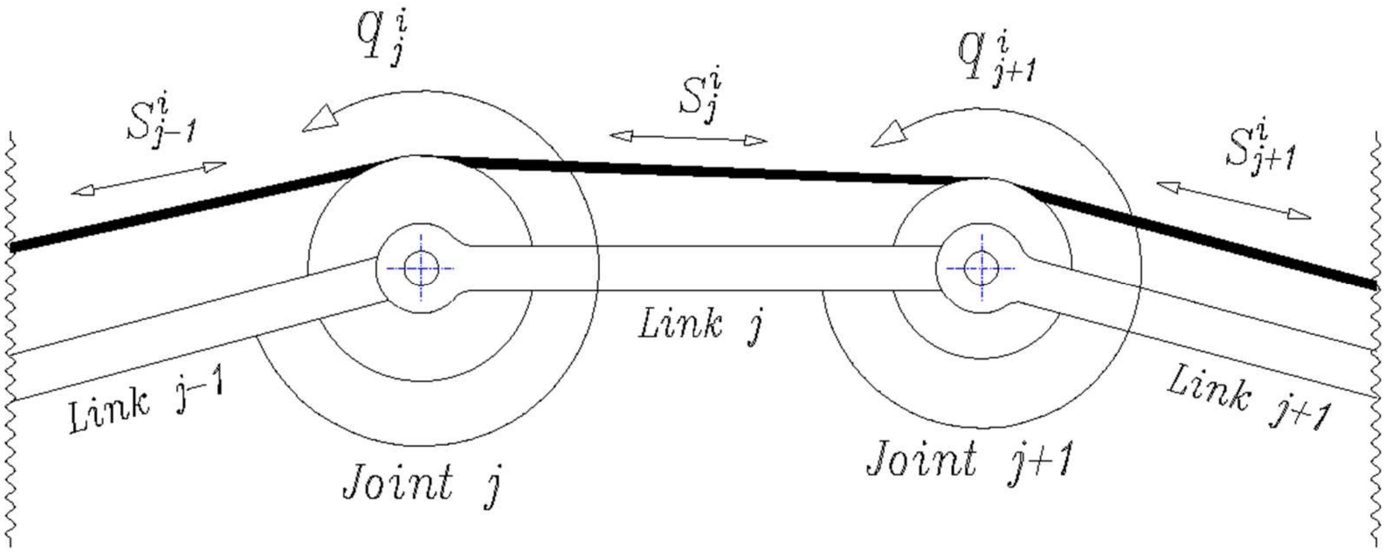

VR Application
Open Loop Control
Without Friction
Compensation
Virtual
Empty
Space
(F=0)
$\mathbf{F}$
$\mathbf{J}^{T}(\mathbf{q})$
+
−
τ
Exos Gravity
Model
τ_G
$\mathbf{X},\dot{\mathbf{X}}$

Distributed model

A detailed model of the transmission system can be made, by dividing the cable in branches, each branch connecting two joints.

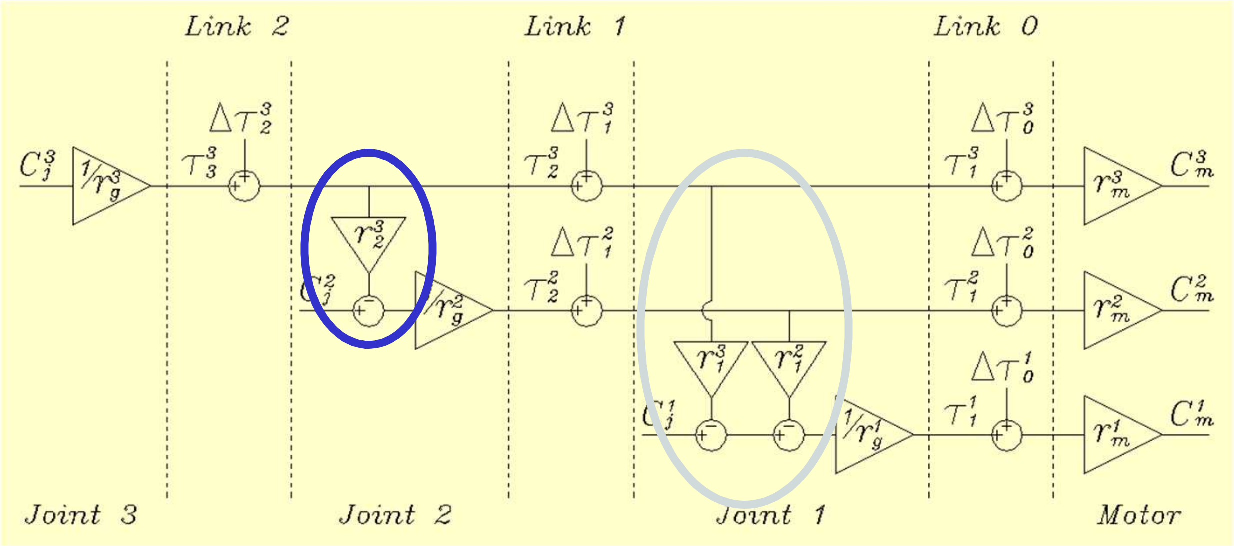
TENDON TENSION LOSS

$$\Delta\tau_j^i = \tau_j^i - \tau_{j+1}^i$$



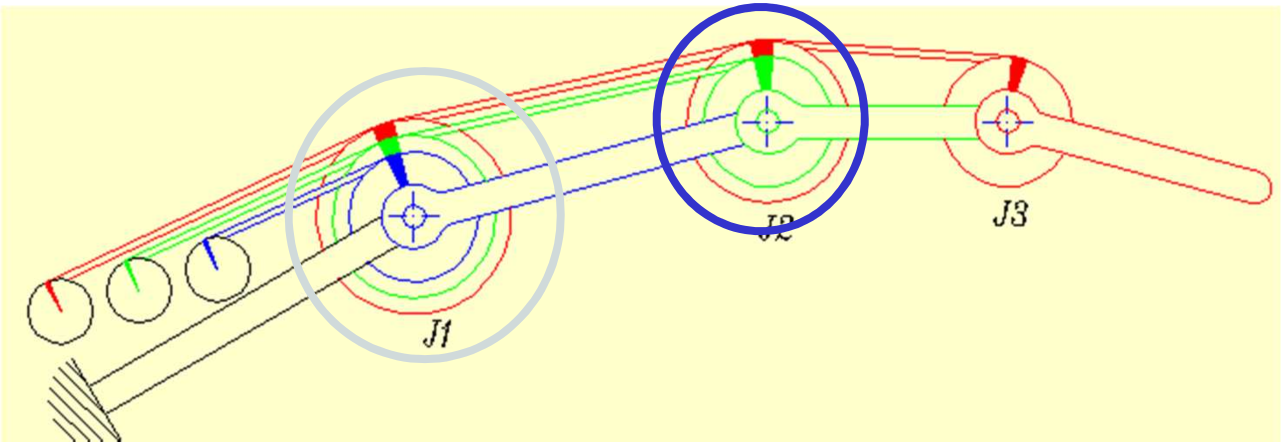
Simone Marcheschi, Antonio Frisoli, Carlo Alberto Avizzano, Massimo Bergamasco , "A Method for Modeling and Controlling Complex Tendon Transmissions in Haptic Interfaces ", Proceedings of IEEE ICRA 2005, April 2005, Barcelona

Static model



Torque transmission along a multi-joint transmission system.

If the cable transmission is not ideal, a tension loss will happen due to dissipative phenomena.



If we consider the transmission i, the loss of tension between joint j and joint j+1 is:

$$\Delta\tau_j^i = \tau_j^i - \tau_{j+1}^i$$

Dissipative effects

The most important dissipative phenomena which affect cable transmissions are the following:

- **friction on pulley supports;**
- **efficiency of cable transmissions;**
- **efficiency of speed-reducers.**

$$M = \begin{cases} M_{ext} & \text{if } n = 0 \text{ and } M_{ext} < \alpha p \\ \beta p + h(n) & \text{if } n \neq 0 \end{cases}$$

$$h(n) = \begin{cases} h_0 & \text{if } n < n_0 \\ h_1 n^{2/3} & \text{if } n \geq n_0 \end{cases}$$

Efficiency of cable transmissions

The efficiency of cable transmission is related to following phenomena:

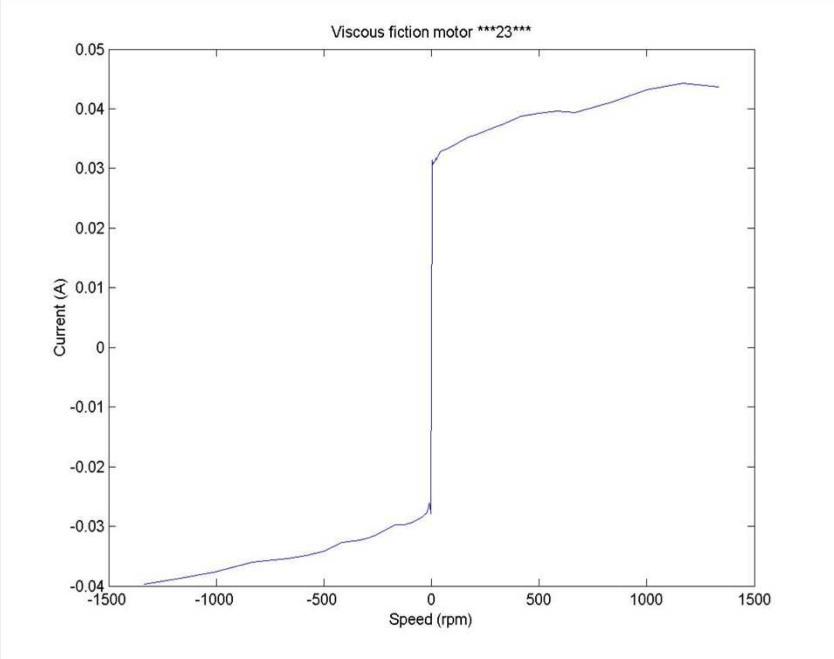
- **elastic sliding between cable and driven pulley;**
- **internal friction between strands which compose the cable;**
- **friction induced by misalignment between cable and pulley.**

Also the efficiency of the reducer should be considered. Direct and inverse reducer efficiency should be considered according to the actual direction of motion.

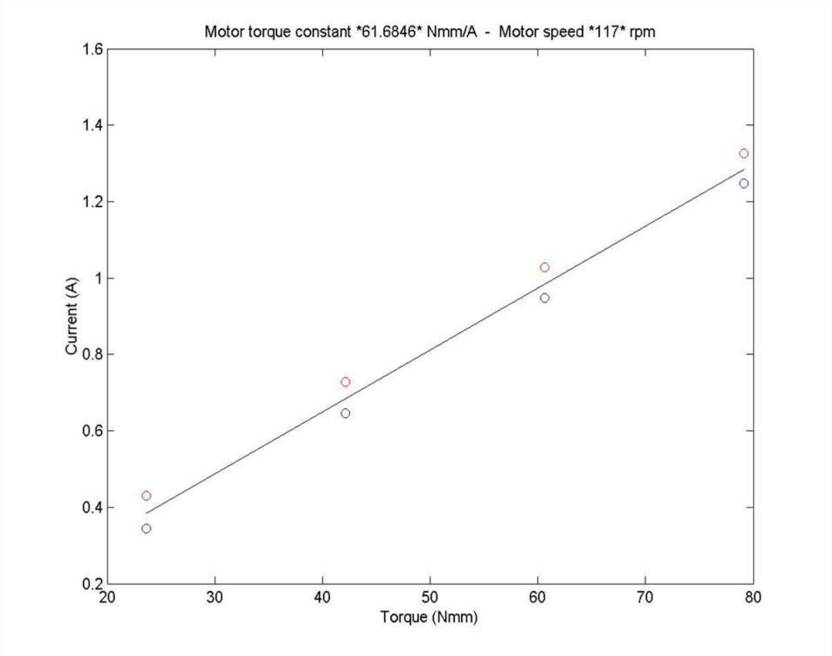
$$M_{out} = \begin{cases} \eta_d \kappa M_{in} & \text{if } M_{out} n_{rid} \geq 0 \\ \frac{\kappa M_{in}}{\eta_i} & \text{if } M_{out} n_{rid} < 0 \end{cases}$$

$$\eta_i = \frac{2\eta_d - 1}{\eta_d}$$

Motor characterization of friction



By recording the current for moving the motor at different speeds with no load, it's possible to define how friction depends on shaft speed



By recording the current for moving the motor with different loads, and at fixed speed, it's possible to define how friction depends on load.

Hypotheses and simplified model

Base operative hypotheses:

- **The efficiency of reducers and cable transmissions can be neglected with respect to the bearings friction**
- **Static friction phenomena are not characterized**
- **Viscous fiction can be expressed as a linear function of bearing speed**
- **All contributions due to the dynamic friction torques of all bearings of a given transmission and placed on a given link can be represented as a single equivalent torque**

All dissipative phenomena can be represented as a loss in the cable tension which goes through a given link j by this relation.

It's a linear function of cable tension and cable speed

$$\Delta\tau_j^i = \beta_j^i \tau_j^i + \upsilon_j^i \dot{S}_j^i$$

Further approximation: the friction forces are considered independent of the cable tension.

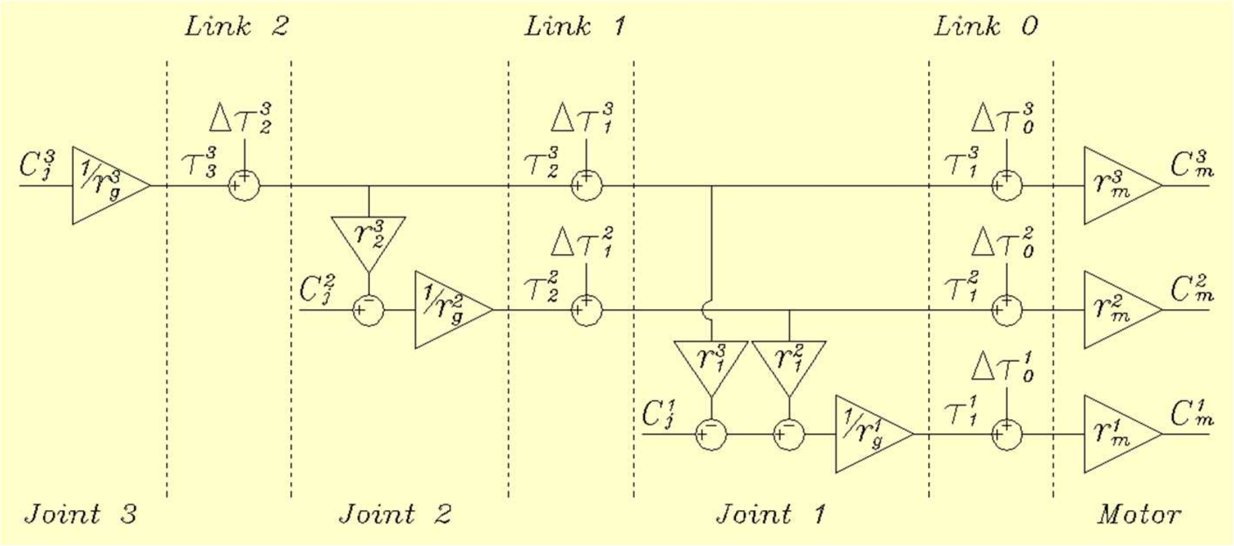
A term to consider the static friction due to the tension of the transmission is also added.

$$\Delta\tau_j^i = \tau_{0,j}^i + \upsilon_j^i \dot{S}_j^i$$

Algorithms for feedforward estimation of compensation torques

Compensation torques can be found, starting by the desired value of joint torques, and can be computed according to

$$\Delta\tau_j^i = \tau_{0,j}^i + \upsilon_j^i \dot{S}_j^i$$



Identication of unknown parameters required

Experimental identification procedure

Exos control

Joint *i* is moved at a given fixed speed

Motor current is recorded

For the other joints/motors, two different strategies can be adopted:

S1:
all remaining motors, but *i*, are controlled at zero speed;

S2:
all remaining joints, but *i*, are controlled at zero speed.

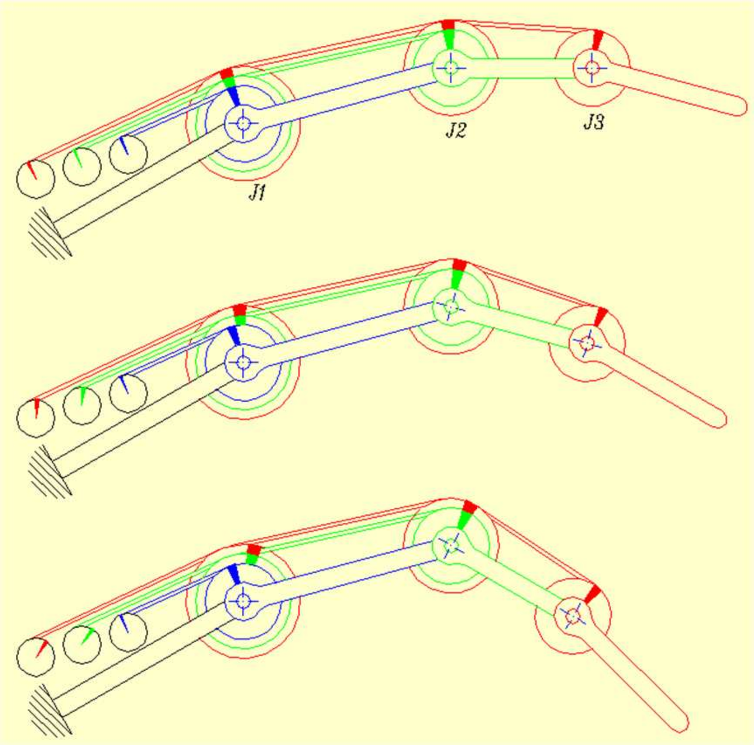
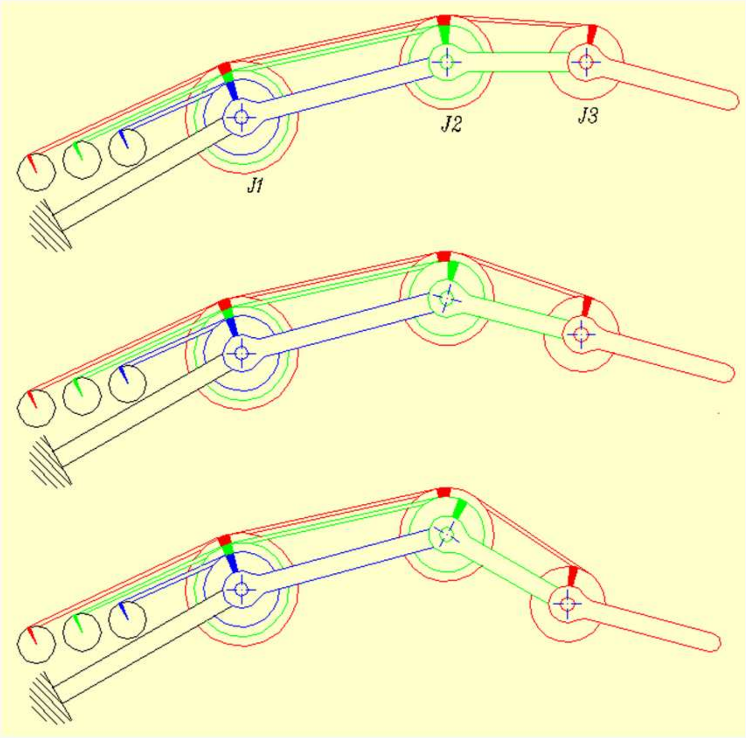
Effects of inertial forces are excluded

For any transmission, the motor torque due to friction in transmission *i*, is given by:

$$C_m^i = C_{m,0}^i + \upsilon^i \dot{q}_m^i$$

Kinematics of coupled transmissions

Joint *i* is moved: **transmissions of joint *k*, with *k* >= *i*, will present a movement**

Blocked joints	**Blocked motors**
	

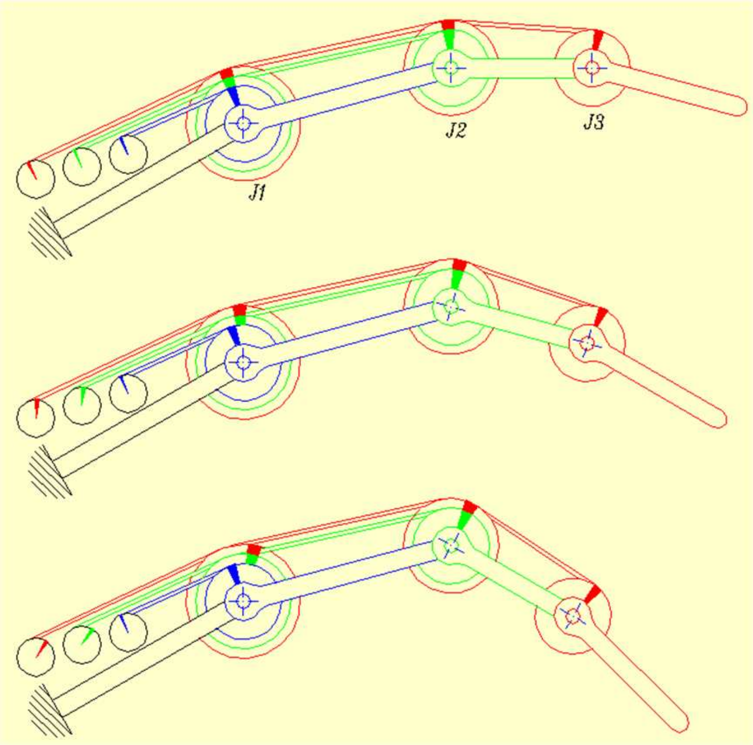
S2. all remaining joints, but i, are controlled at zero speed.

S1. all remaining motors, but i, are controlled at zero speed;

Condition S2

Joint *i* is moved: transmissions of joint *k*, with *k* >= *i*, will present a movement

Blocked joints



For $i < j$

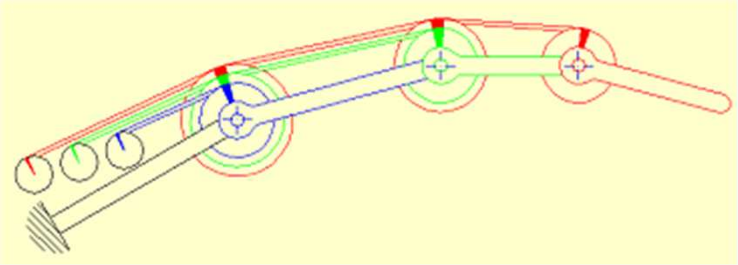
$$\dot{q}_{mi} = 0$$

For $i \geq j$

$$\dot{q}_{mi} = k_{ij}\dot{q}_j$$

$$\dot{\mathrm{q}} = \begin{bmatrix} 0 \\ .. \\ \dot{q}_i \\ .. \\ 0 \\ 0 \end{bmatrix}$$

$$\dot{\mathrm{q}}_{\mathrm{m}} = K_T\dot{\mathrm{q}} = \begin{vmatrix} k_{11} & 0 & 0 & \dots & 0 \\ k_{21} & k_{22} & 0 & \dots & 0 \\ k_{31} & k_{32} & k_{33} & \dots & 0 \\ \dots & \dots & \dots & \dots & 0 \\ k_{n1} & k_{n2} & k_{n3} & \dots & k_{nn} \end{vmatrix} \dot{\mathrm{q}}$$



Energetic balance of losses

If we assume that at the motor side:

$$\tau^i = \tau_0^i + \nu^i \dot{q}_m^i$$

Tendon loss at each joint:

$$\Delta\tau_j^i = \tau_{0,j}^i + \nu_j^i \, \dot{S}_j^i$$

$$\dot{S}_j^i = k'^i_j \dot{q}_m^i$$

Estimation of power dissipated:

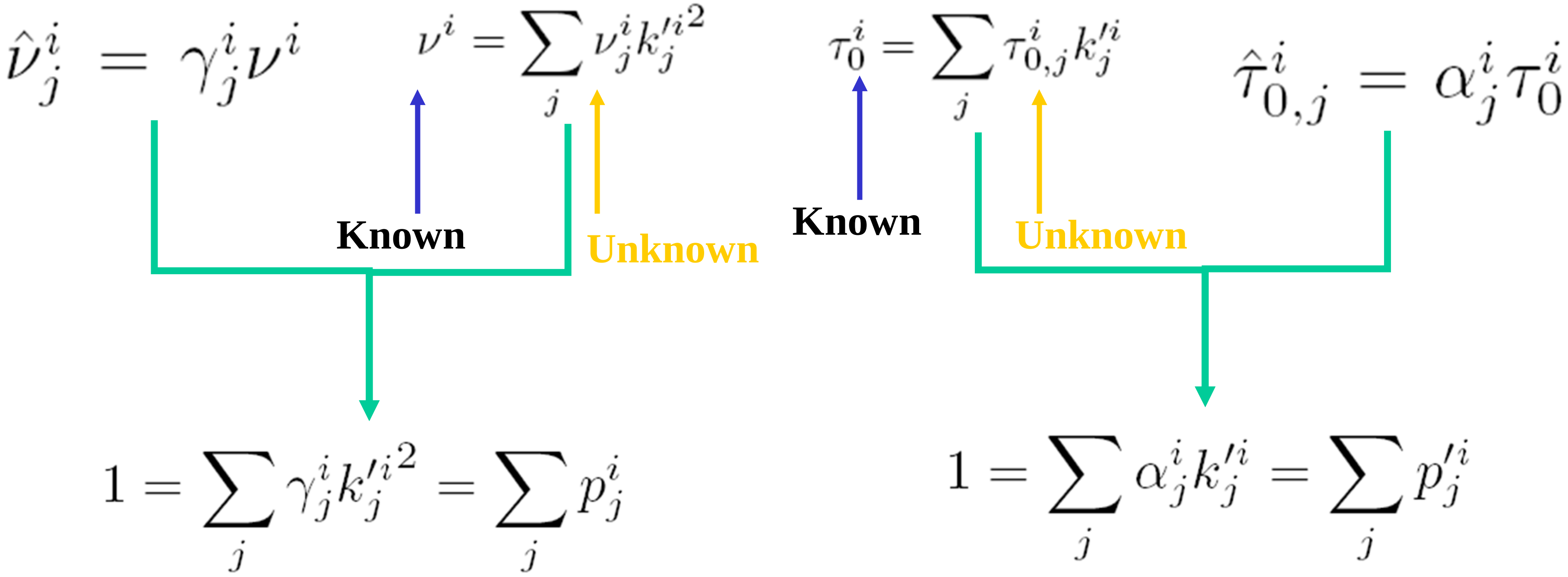
$$E_{loss,i} = \boxed{\tau_0^i} \dot{q}_m^i + \boxed{\nu^i} \dot{q}_m^{i\,2} = \dot{q}_m^i \boxed{\sum_j \tau_{0,j}^i k'^i_j} + \dot{q}_m^{i\,2} \boxed{\sum_j \nu_j^i k'^{i\,2}_j}$$

This implies:

$$\underset{\textbf{Known}}{\underset{\uparrow}{\nu^i}} = \sum_j \underset{\textbf{Unknown}}{\underset{\uparrow}{\nu_j^i k'^{i\,2}_j}} \qquad \underset{\textbf{Known}}{\underset{\uparrow}{\tau_0^i}} = \sum_j \underset{\textbf{Unknown}}{\underset{\uparrow}{\tau_{0,j}^i k'^i_j}}$$

Energetic balance of losses

If we use the following model



$$\hat{\nu}^i_j = \gamma^i_j \nu^i \qquad \nu^i = \sum_j \nu^i_j k'^{i\,2}_j \qquad \tau^i_0 = \sum_j \tau^i_{0,j} k'^i_j \qquad \hat{\tau}^i_{0,j} = \alpha^i_j \tau^i_0$$

Known

Unknown

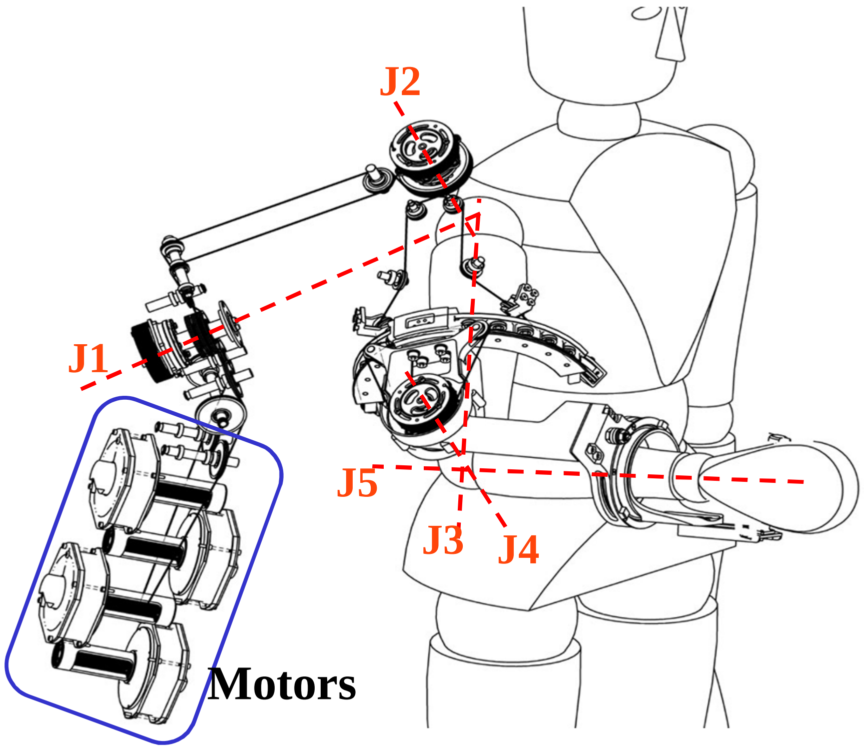
Known

Unknown

$$1 = \sum_j \gamma^i_j k'^{i\,2}_j = \sum_j p^i_j \qquad 1 = \sum_j \alpha^i_j k'^i_j = \sum_j p'^i_j$$

Physical interpretation: the terms p^i_j and p'^i_j represent the percentage losses that we have along the transmission due to friction.

Exos transmission system



$$\Delta\tau^i_j = \tau^i_{0,j} + \upsilon^i_j \dot{S}^i_j$$

$$1=\sum_j \gamma^i_j k^{i2}_j = \sum_j p^i_j \qquad 1=\sum_j \alpha^i_j k^i_j = \sum_j p'^i_j$$

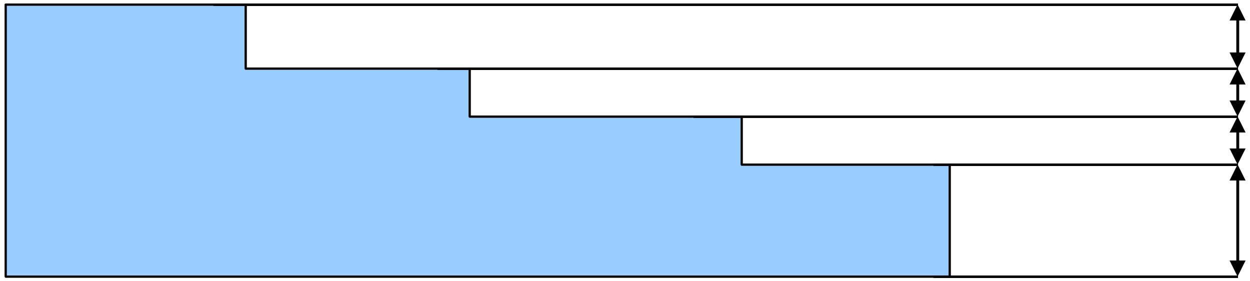
Experimental identification of:

$$\tau^i = \tau^i_0 + \nu^i \dot{q}^i_m$$

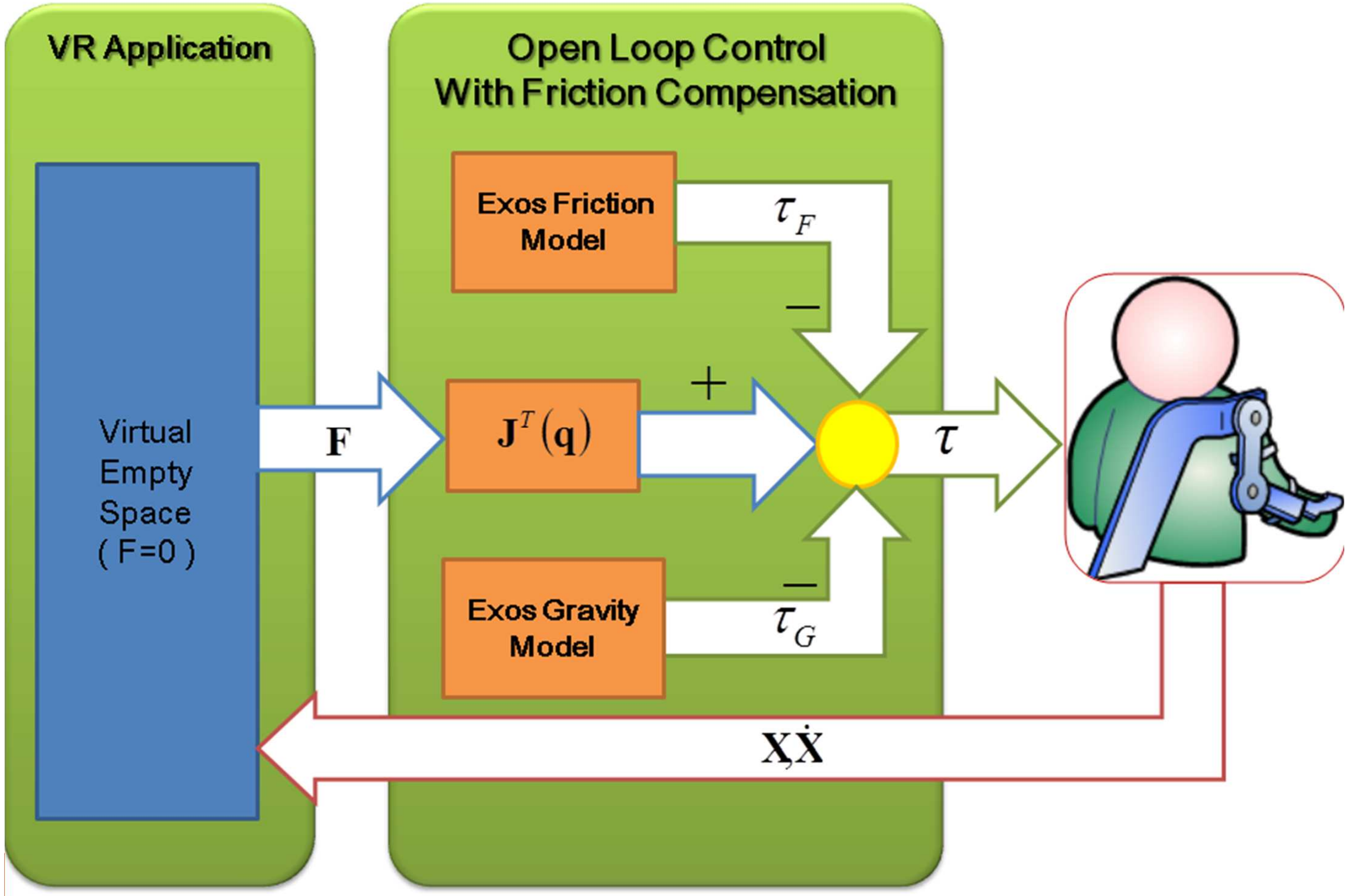
Estimation of percentage losses by design

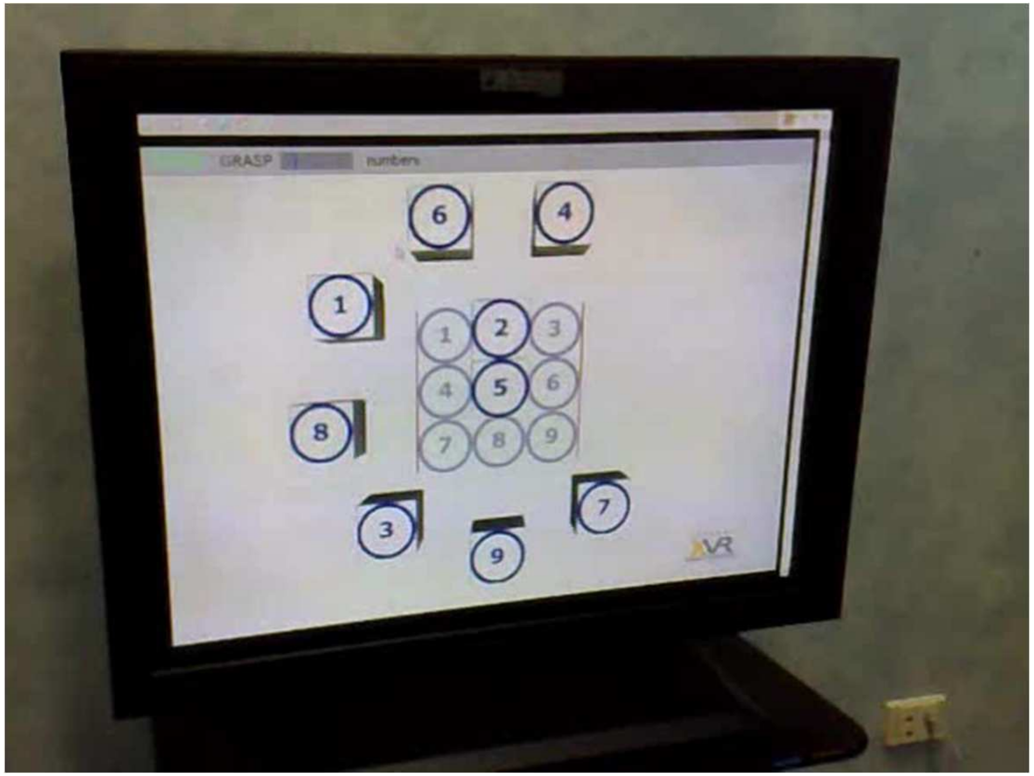
$$\hat{\nu}^i_j = \gamma^i_j \nu^i \qquad \hat{\tau}^i_{0,j} = \alpha^i_j \tau^i_0$$

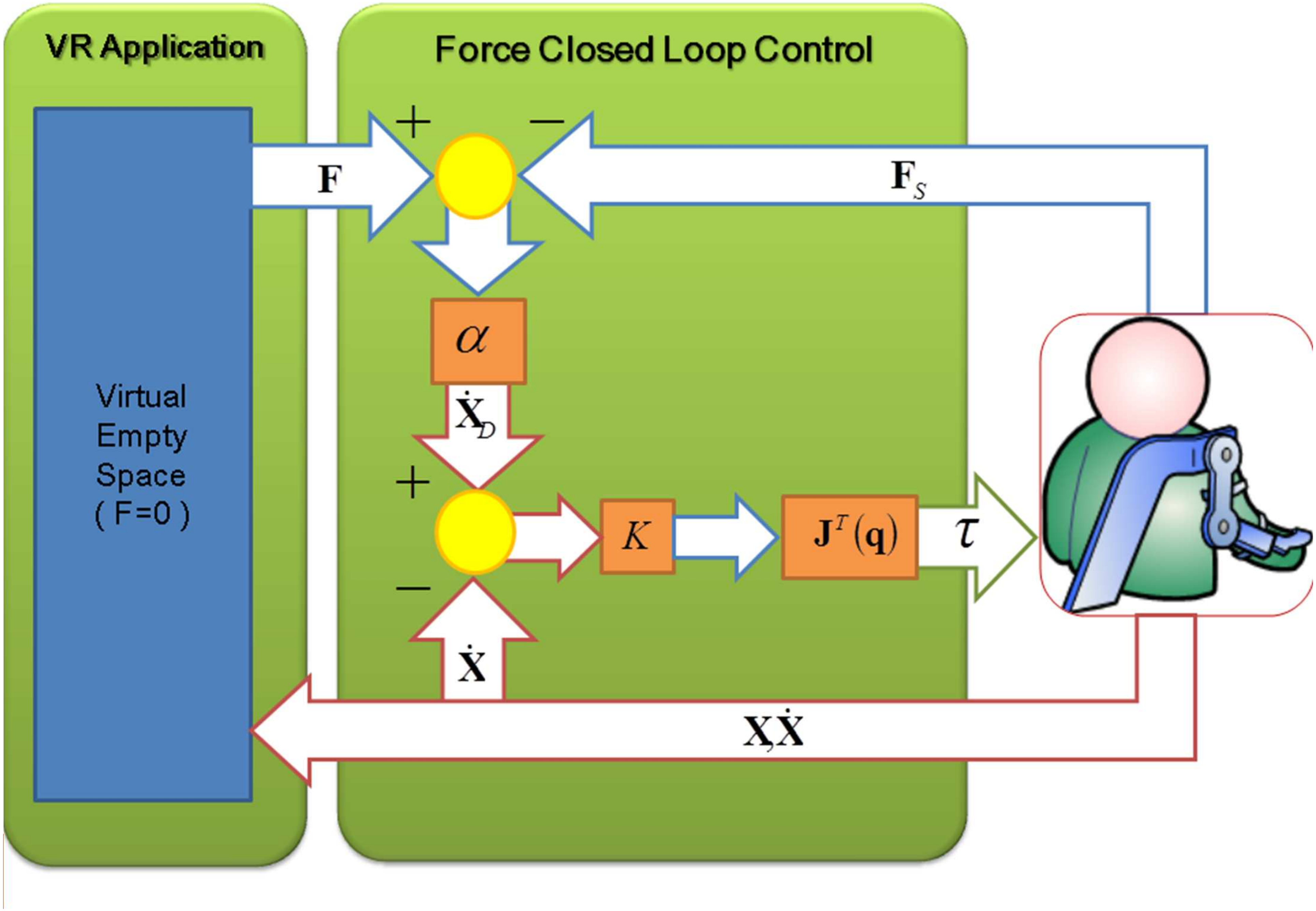
Tension loss in percentage



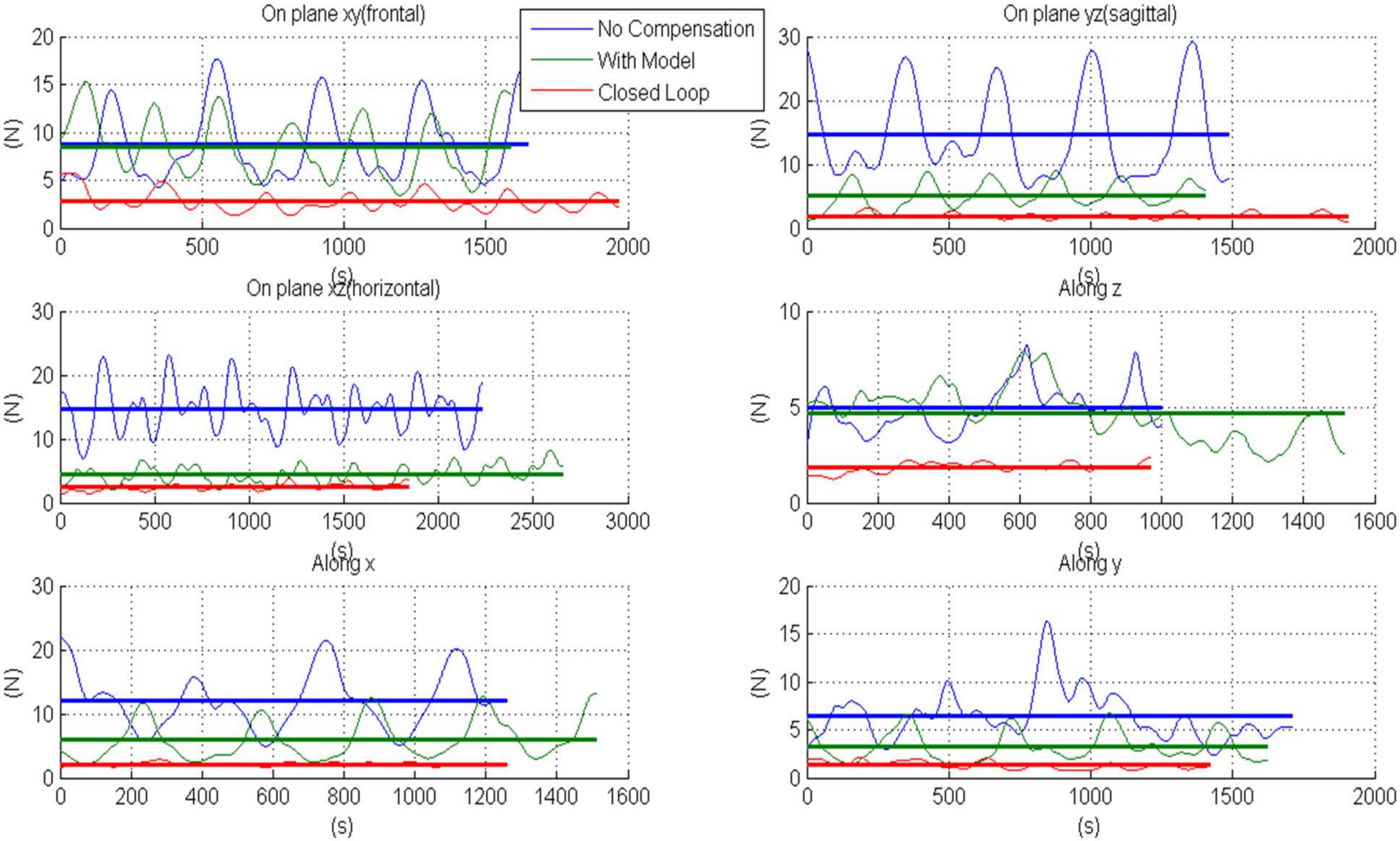
p^4_1 20% +
p^4_2 30% +
p^4_3 10% +
p^4_4 40% =
100%


VR Application
Virtual Empty Space (F=0)
$\mathbf{F}$
Open Loop Control With Friction Compensation
Exos Friction Model
τ_F
$-$
$\mathbf{J}^T(\mathbf{q})$
$+$
τ
$-$
τ_G
Exos Gravity Model
$\mathbf{X}, \dot{\mathbf{X}}$

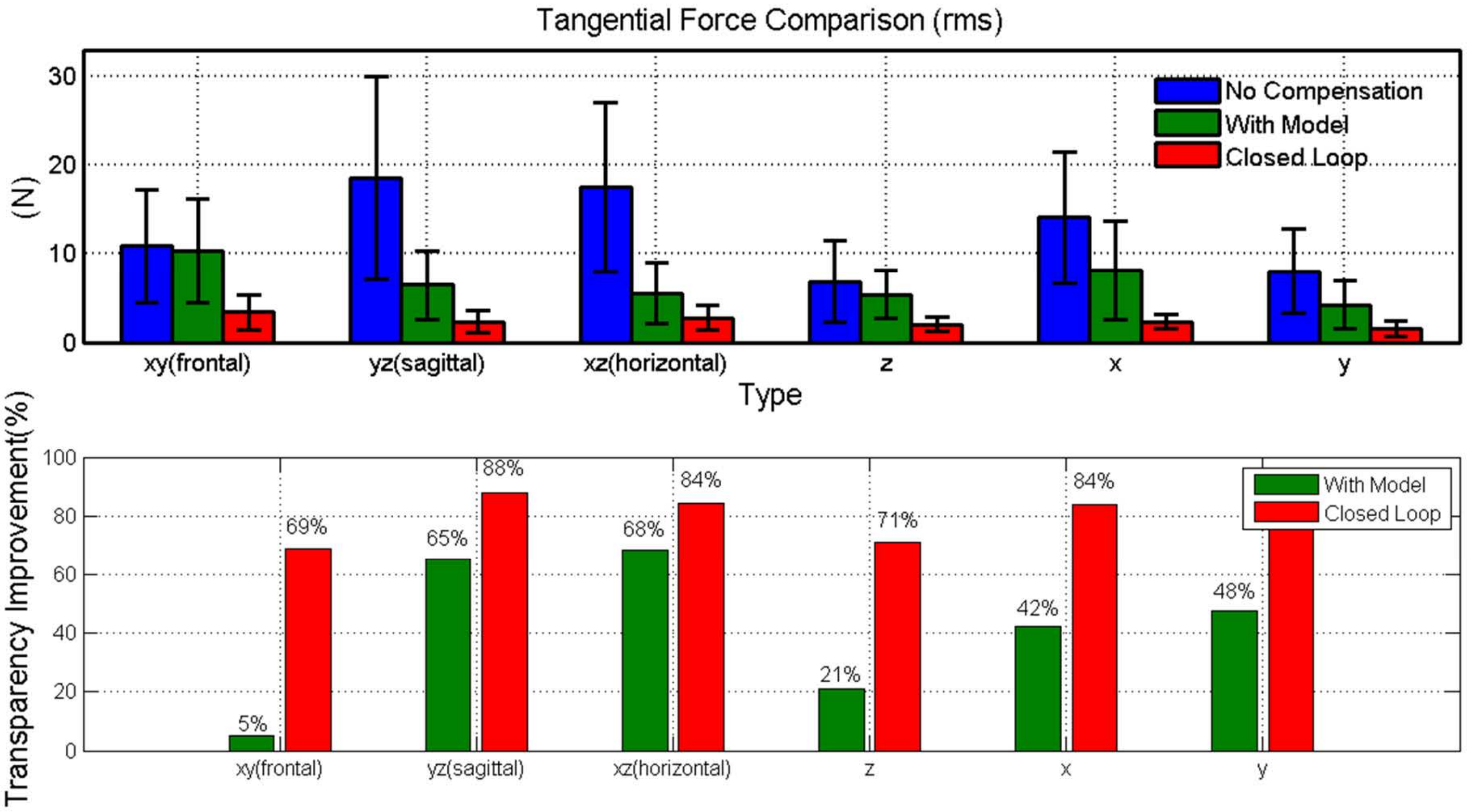

GRASP
numbers
6
4
1
2
3
1
5
4
6
7
8
9
8
3
9
7
XVR


VR Application
Force Closed Loop Control
Virtual
Empty
Space
(F=0)
+
−
$\mathbf{F}$
$\mathbf{F}_S$
α
$\dot{\mathbf{X}}_D$
+
−
K
$\mathbf{J}^T(\mathbf{q})$
τ
$\dot{\mathbf{X}}$
$\mathbf{X}, \dot{\mathbf{X}}$

Force performance of the L-Exos system

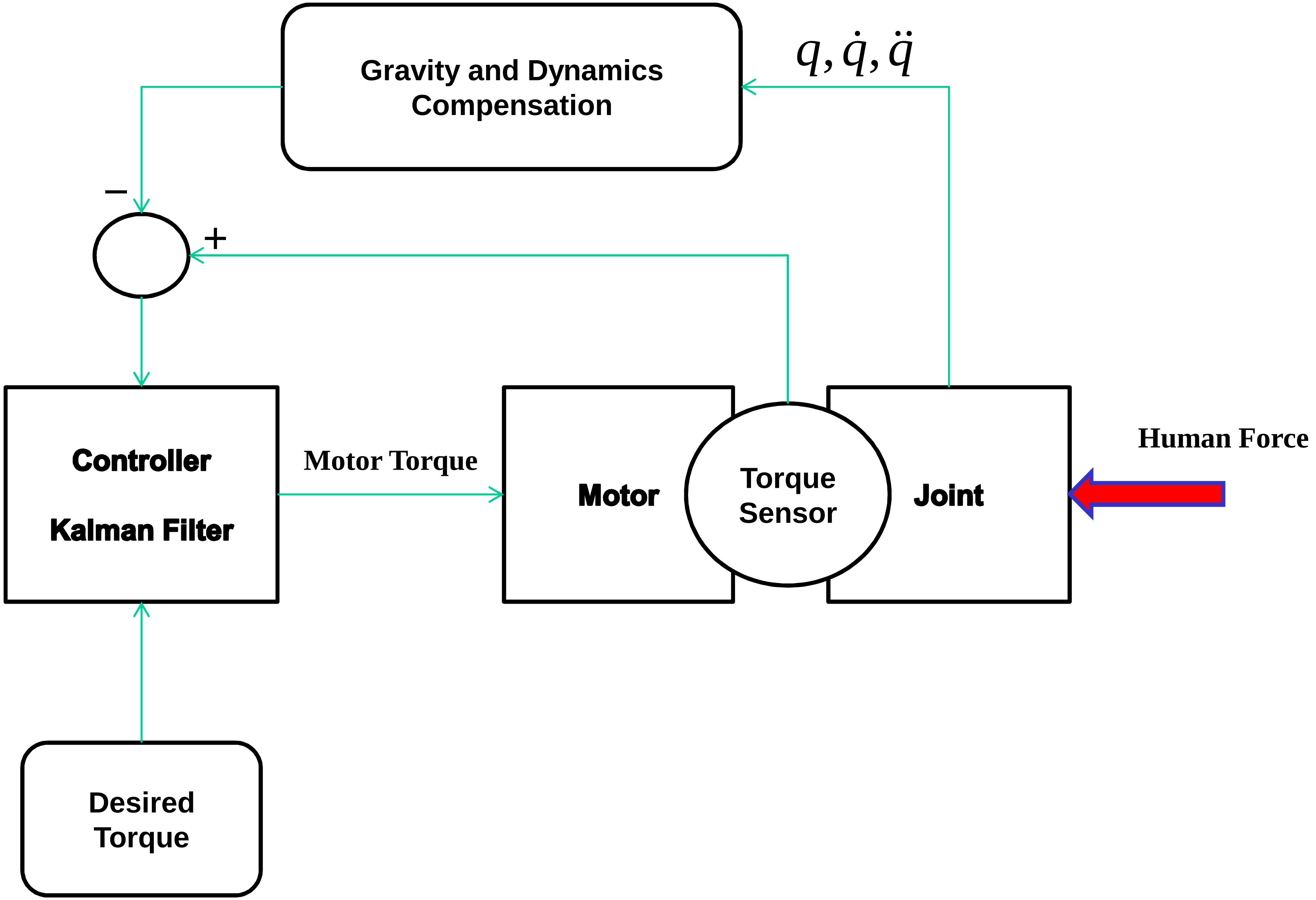


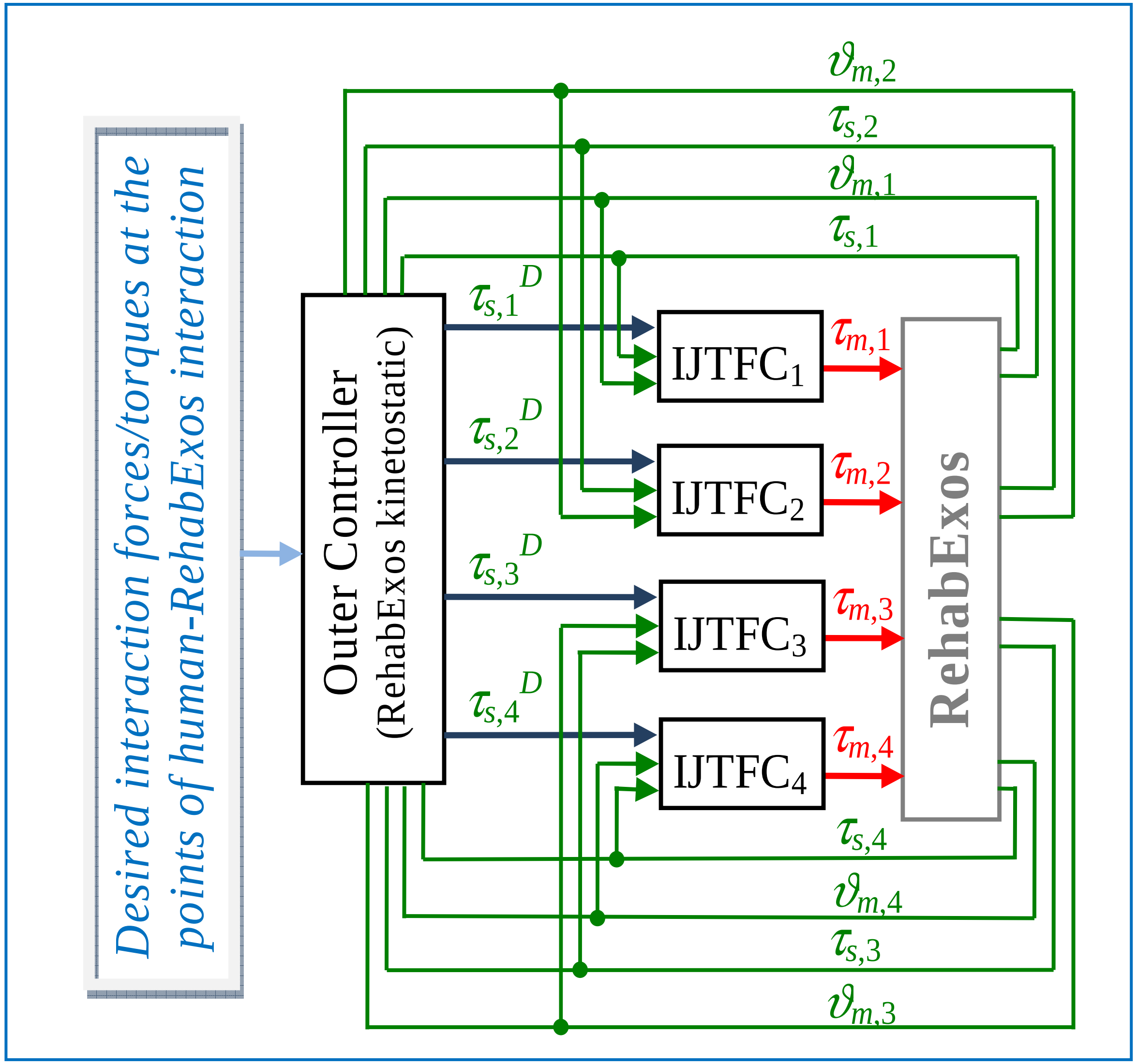
Error in force in different conditions

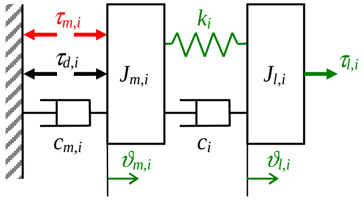


THE REHAB-EXOS SYSTEM

General control scheme

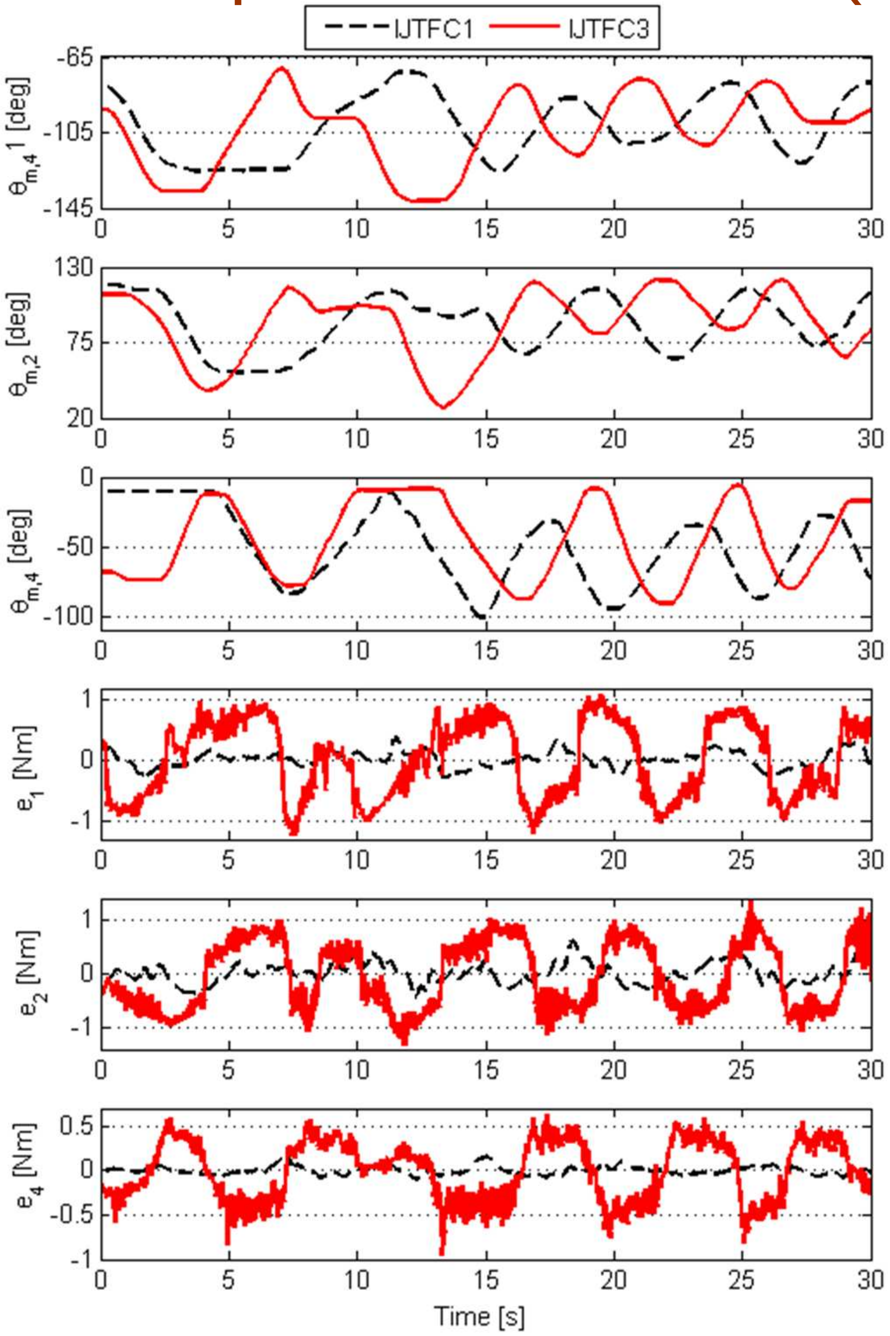






Vertechy, R., Frisoli A, Solazzi M., Dettori A., Bergamasco M., Linear-Quadratic-Gaussian Torque Control Application to a Flexible Joint of a Rehabilitation Exoskeleton, IEEE ICRA International Conference on Robotics and Automation, Anchorage, Alaska, 2010

Experimental values (1/2)

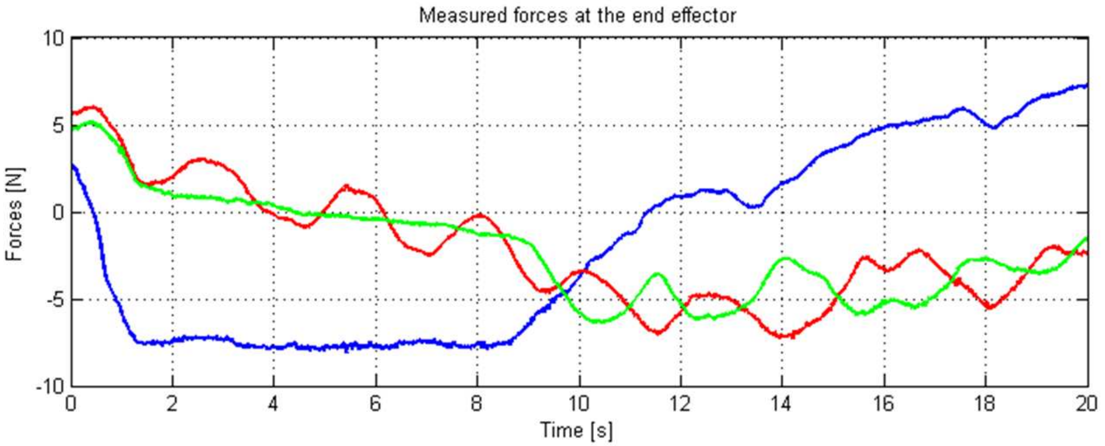


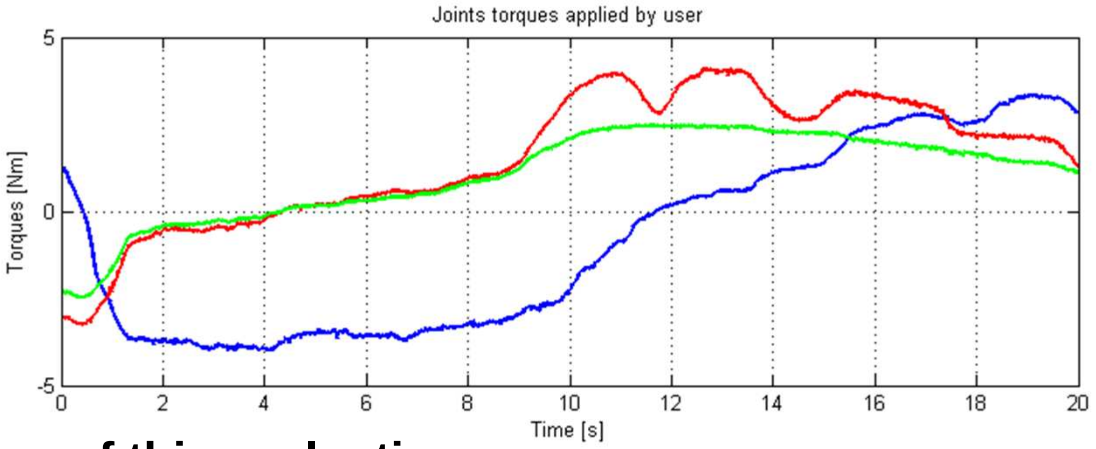
Comparison of

IJTFC1 state space model of dynamics

IJTFC3 Standard PID force control

Experimental values (2/2)





Current limitations of this evaluation are:

- **Only 50% dynamic compensation provided for joint #1**
- **20% feedforward compensation for joint #2**
- **0% for joint #3**
- **Inperfect calibration of joint torque sensor**

Conclusions

- In exoskeleton design both low impedance and high impedance design might be efficiently used

Impedance designs

PROs

- **Backdrivable mechanics**
- **Delocalization of actuation**

CONTRAs

- **Joint coupling by tendon transmissions**
- **Difficulty in compensation and estimation of static friction effects**
- **Dynamic compensation**

Admittance designs

PROs

- **System safety is motors are turned off**
- **Precise control of dynamics/friction**
- **Joint torque monitoring**

CONTRAs

- **Need of force sensors in the structure**
- **Possible limitation in maximum speed in high reduction designs**

thank you!

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