POLITECNICO DI MILANO

Upper Limb Mechanical Impedance Variability Estimation by Inverse Dynamics and Torque-Less Activation Modes

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2nd IMSD, Stuttgart, Germany, May 29-June 1, 2012

Outline

- Rotorcraft-Pilot Couplings
- Modeling Approach
  - Inverse Kinematics
  - Inverse Dynamics
  - Muscle Model and Muscular Activation
  - Equivalent Impedance
- Numerical Results
- Conclusions and Future Work

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Aeroelastic Rotorcraft/Pilot Couplings

Aircraft/Rotorcraft-Pilot Couplings are

"unintentional (inadvertent) sustained or uncontrollable vehicle oscillation characterized by a mismatch between the pilot's mental model of the vehicle dynamics and the actual vehicle dynamics." (Mc Ruer)

ARISTOTEL: project sponsored by EC 7th FP led by TUDelft [1]

Aircraft and Rotorcraft Pilot Couplings Tools and Techniques for Alleviation and Detection
http://www.aristotelproject.eu/

ARISTOTEL

This presentation is related to research on biomechanical modeling of pilot's equivalent impedance.

[1] M. D. Pavel, J. Malecki, B. DangVu, P. Masarati, M. Gennaretti, M. Jump, H. Smaili, A. Ionita, L. Zaicek, "A Retrospective Survey of Adverse Rotorcraft Pilot Couplings in European Perspective", 68th AHS Forum, Fort Worth, Texas, May 1-3, 2012.

Aeroelastic Rotorcraft/Pilot Couplings

Approach within ARISTOTEL

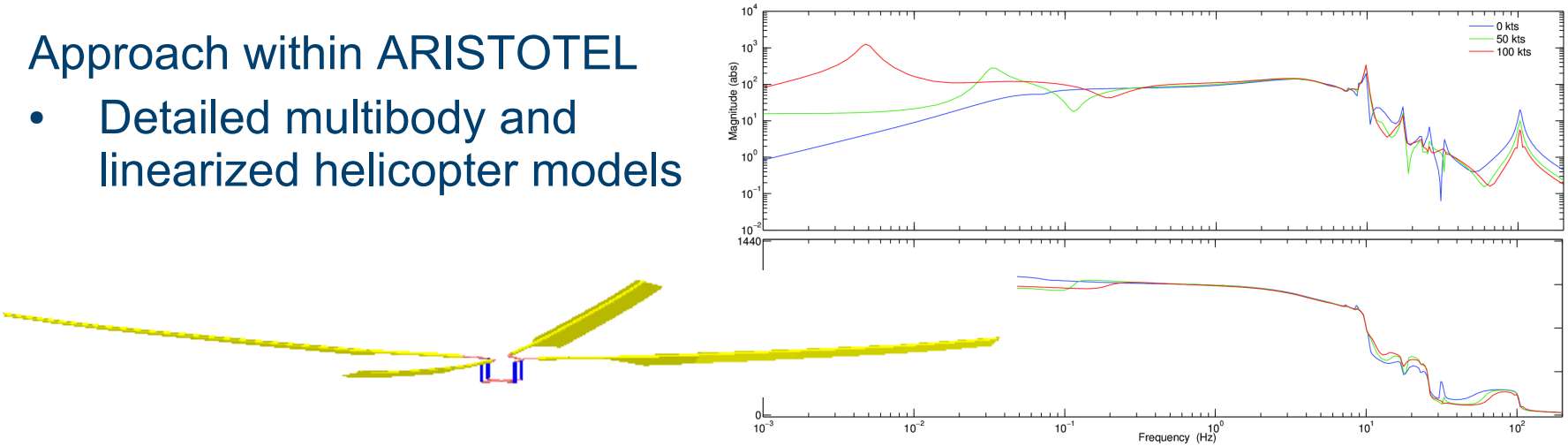
- Develop aeroelastic models of aircraft (e.g. [1])
  - multibody & linearized models
- **Develop models of the voluntary/involuntary pilot action**
  - transfer functions identified from experiments
  - **multibody biomechanical models**
- Couple vehicle and pilot models
- Predict impact of pilot interaction on stability and performance
- Determine design guidelines for RPC-free aircraft
- Substantial experimental activity (mostly in flight simulators) in support to the project

[1] V. Muscarello, P. Masarati, G. Quaranta, "Multibody Analysis of Rotorcraft-Pilot Coupling", IMSD 2012, Stuttgart, Germany, May 29-June 1, 2012.

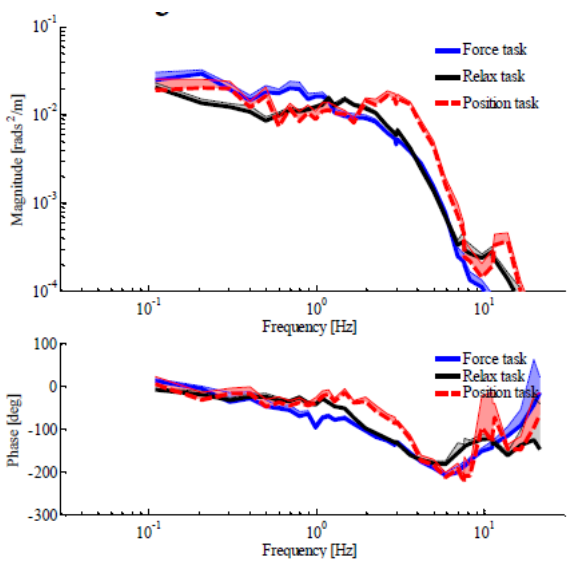
Aeroelastic Rotorcraft/Pilot Couplings

Approach within ARISTOTEL

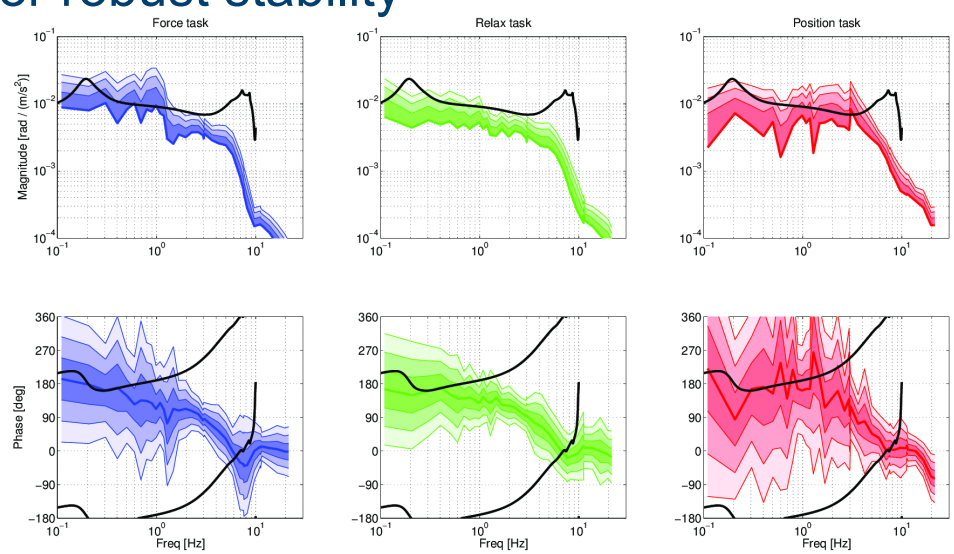
- Detailed multibody and linearized helicopter models



- Experimental pilot BDFT



Numerical & graphical criteria for robust stability



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  - Inverse Dynamics
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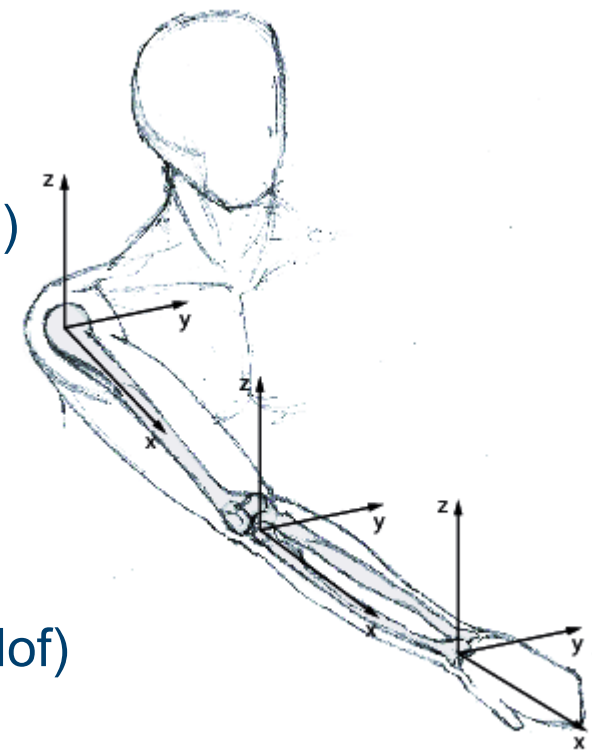
Modeling Approach

Multibody model of the upper limb
redundant coordinates approach

- 4 rigid bodies (24 variables):
  - humerus, radius, ulna, hand (not detailed)

- articulations (17 passive constr.): $\phi(x)=0$
  - shoulder complex: spherical joint (-3 dof)
  - humeroulnar joint: revolute joint (-5 dof)
  - humeroradial joint: spherical joint (-3 dof)
  - proximal and distal radioulnar: inline (-2 dof)
  - carpal complex: universal (-4 dof)



- muscles: 25 viscoelastic rods
  (constitutive law derived from Pennestrì et al., 2007, [1])
  for 7 motor joints $\theta=\theta(x) \quad \backslash \quad \phi_{/x}\theta^{+}_{/x}=0$

[1] E. Pennestrì, R. Stefanelli, P. P. Valentini, and L. Vita. Virtual musculo-skeletal model for the biomechanical analysis of the upper limb. Journal of Biomechanics, 40(6):1350–1361, 2007.

Modeling Approach

- Determine the kinematics of the limb for prescribed hand motion

$$\psi(x)=\alpha(t)$$

(underdetermined problem solved by local optimization)

  - Inverse kinematics at positions level

$$J_p(x)=V(\theta(x))+\lambda^T\phi(x)+\mu^T(\psi(x)-\alpha(t))$$

  - Inverse kinematics at velocity level

$$J_v(x)=(\dot{x}-\dot{x}_r)^T M(\dot{x}-\dot{x}_r)+2\lambda^T\dot{\phi}(x)+2\mu^T(\dot{\psi}(x)-\dot{\alpha}(t))$$

  - Inverse kinematics at acceleration level

$$J_a(x)=(\ddot{x}-\ddot{x}_r)^T M(\ddot{x}-\ddot{x}_r)+2\lambda^T\ddot{\phi}(x)+2\mu^T(\ddot{\psi}(x)-\ddot{\alpha}(t))$$

- Determine the motor torques (fully determined problem)

$$\phi_{/x}^T\lambda+\theta_{/x}^T c=f-M\ddot{x}$$

- Determine the muscular activations (minimal norm) for motor torques

$$c=(\theta_{/x}^T)^+ l_{/x}^T f_m(l(x),\dot{l}(x,\dot{x}),a)$$

- Determine the equivalent compliance (linearization, reduction)

Modeling Approach

- prescribed hand motion

$$\psi(x)=\alpha(t)$$

- ergonomy cost function subjected to **passive** and **prescribed motion** constraints

$$J_p(x)=V(\theta(x))+\lambda^T\phi(x)+\mu^T(\psi(x)-\alpha(t))$$

- inverse kinetostatics **at position level**

$$V_{/x}(\theta(x)-\theta_r)+\phi_{/x}^T\lambda+\psi_{/x}^T\mu=f$$
$$\phi(x)=0$$
$$\psi(x)=\alpha(t)$$

- cost function penalizes distance from “maximum comfort”

$$\Delta\theta=\theta-\frac{\theta_{max}-\theta_{min}}{2}$$

- high-(even)-order plus quadratic terms for positive definiteness and boundary avoidance

Modeling Approach

- passive constraints and prescribed hand motion **first derivative**

$$\dot{\phi}(x) = \phi_{/x}\dot{x} = 0$$
$$\dot{\psi}(x) = \psi_{/x}\dot{x} = \dot{\alpha}(t)$$

- least-squares distance from reference velocity

$$J_v(x) = (\dot{x} - \dot{x}_r)^T M(\dot{x} - \dot{x}_r) + 2\lambda^T \dot{\phi}(x) + 2\mu^T(\dot{\psi}(x) - \dot{\alpha}(t))$$

- inverse kinematics **at velocity level**

$$M\dot{x} + \phi_{/x}^T \lambda + \psi_{/x}^T \mu = M\dot{x}_r$$
$$\phi_{/x}\dot{x} = 0$$
$$\psi_{/x}\dot{x} = \dot{\alpha}(t)$$

- reference velocity from numerical differentiation of position (BDF)

$$\dot{x}_r = \frac{x_k - x_{k-1}}{\Delta t}$$

- linear problem

Modeling Approach

- passive constraints and prescribed hand motion **second derivative**

$$\ddot{\phi}(x)=\phi_{/x}\ddot{x}+(\phi_{/x}\dot{x})_{/x}\dot{x}=0$$
$$\ddot{\psi}(x)=\psi_{/x}\ddot{x}+(\psi_{/x}\dot{x})_{/x}\dot{x}=\ddot{\alpha}(t)$$

- least-squares distance from reference acceleration

$$J_a(x)=(\ddot{x}-\ddot{x}_r)^T M(\ddot{x}-\ddot{x}_r)+2\lambda^T\ddot{\phi}(x)+2\mu^T(\ddot{\psi}(x)-\ddot{\alpha}(t))$$

- inverse kinematics **at acceleration level**

$$M\ddot{x}+\phi_{/x}^T\lambda+\psi_{/x}^T\mu=M\ddot{x}_r$$
$$\phi_{/x}\ddot{x}=-(\phi_{/x}\dot{x})_{/x}\dot{x}$$
$$\psi_{/x}\ddot{x}=\ddot{\alpha}(t)-(\psi_{/x}\dot{x})_{/x}\dot{x}$$

- reference acceleration from numerical differentiation of velocity (BDF)

$$\ddot{x}_r=\frac{\dot{x}_k-\dot{x}_{k-1}}{\Delta t}$$

- linear problem, **same Jacobian matrix of velocity problem**

Modeling Approach

- motor torques (fully determined problem)

$$\phi_{/x}^{T}\lambda+\theta_{/x}^{T}c=f-M\ddot{x}$$

- Formally:

$$\left(\theta_{/x}^{T}\right)^{+}\left(\phi_{/x}^{T}\lambda+\theta_{/x}^{T}c\right)=\left(\theta_{/x}^{T}\right)^{+}\left(f-M\ddot{x}\right)$$

implies

$$\underbrace{\left(\theta_{/x}^{T}\right)^{+}\phi_{/x}^{T}}_{0}\lambda+\underbrace{\left(\theta_{/x}^{T}\right)^{+}\theta_{/x}^{T}}_{I}c=\left(\theta_{/x}^{T}\right)^{+}\left(f-M\ddot{x}\right)$$

i.e.

$$c=\left(\theta_{/x}^{T}\right)^{+}\left(f-M\ddot{x}\right)$$

Modeling Approach

- muscular activation
  - muscle model

$$f_m = f_0\left(f_1(x) f_2(v) a + f_3(x)\right) \qquad x = l/l_r \qquad v = \dot{l}/V_r$$

"a" is the muscular activation 0 ≤ a ≤ 1

- minimal norm activation

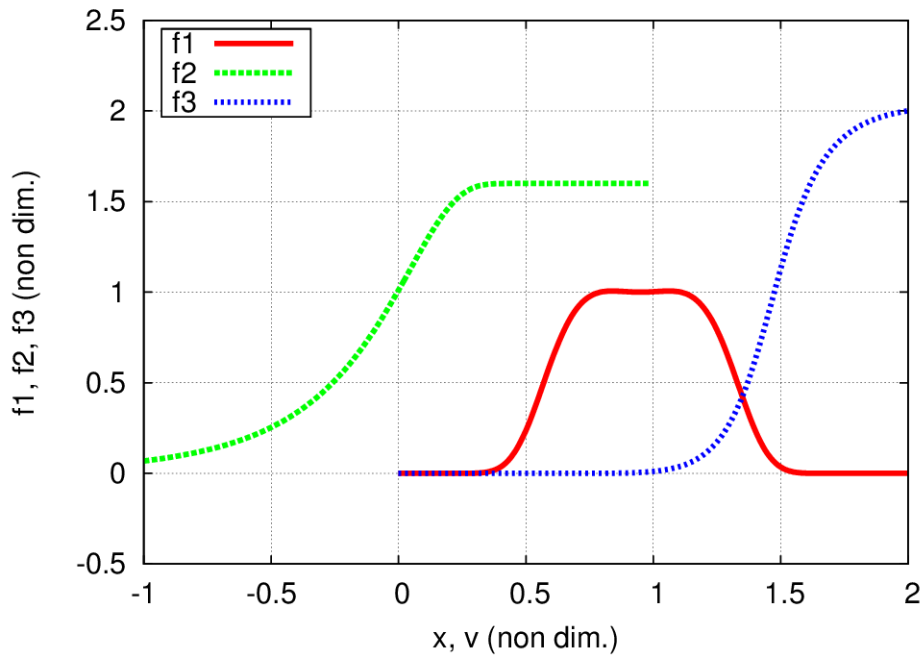
$$J(a) = \frac{1}{2} a^T a$$

- subjected to

$$c = \left(\theta_{/x}^T\right)^+ l_{/x}^T \left(f_{m0} + F_m a\right)$$
$$0 \le a \le 1$$

namely

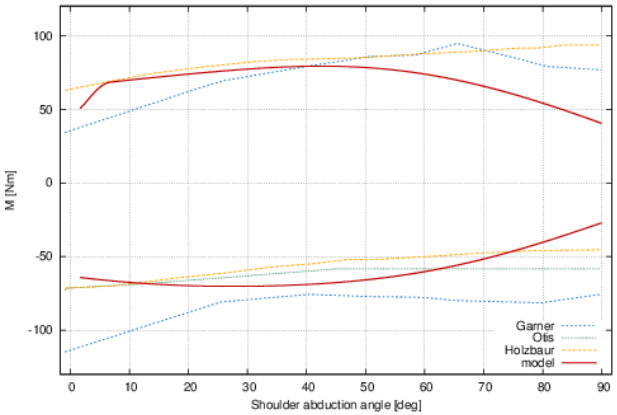
$$A a = b$$
$$0 \le a \le 1$$



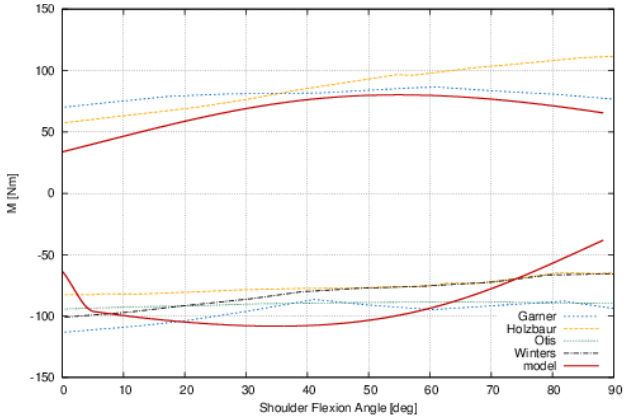
Modeling Approach

- muscle force verification (maximal isometric force vs. joint rotation)

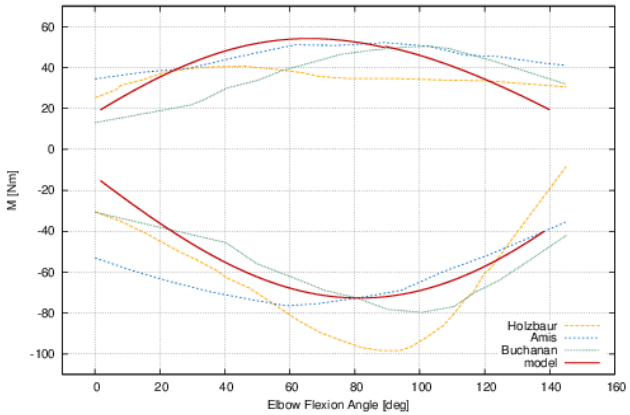
shoulder abduction



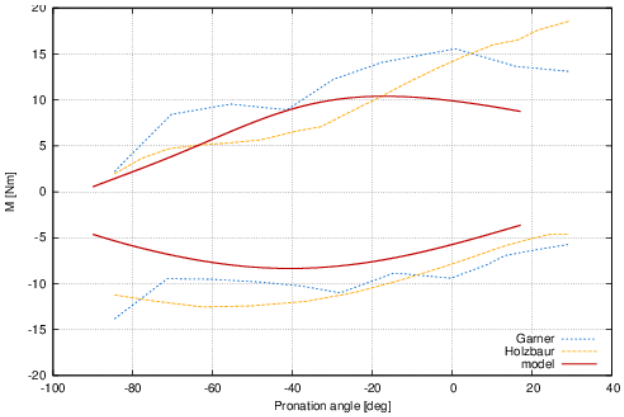
shoulder flexion



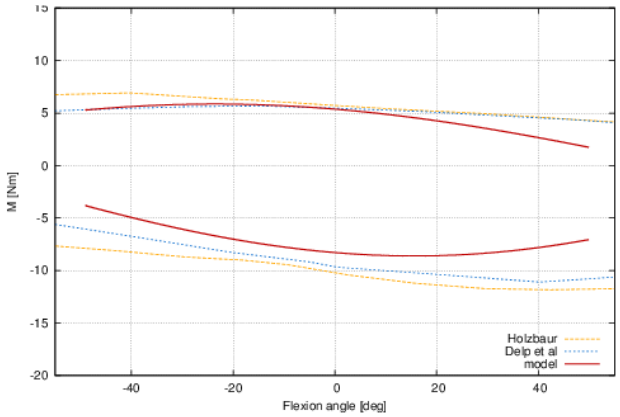
elbow flexion



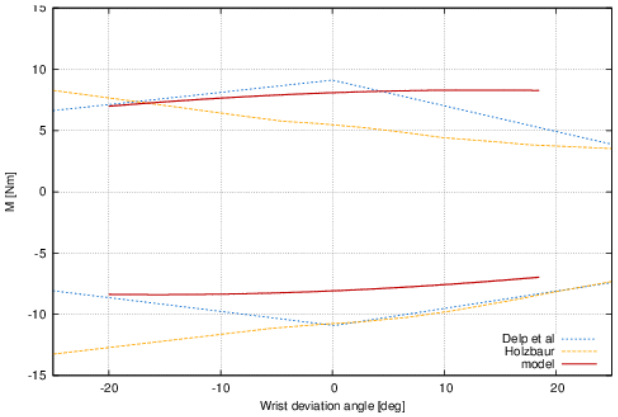
prono-supination



wrist flexion



wrist deviation



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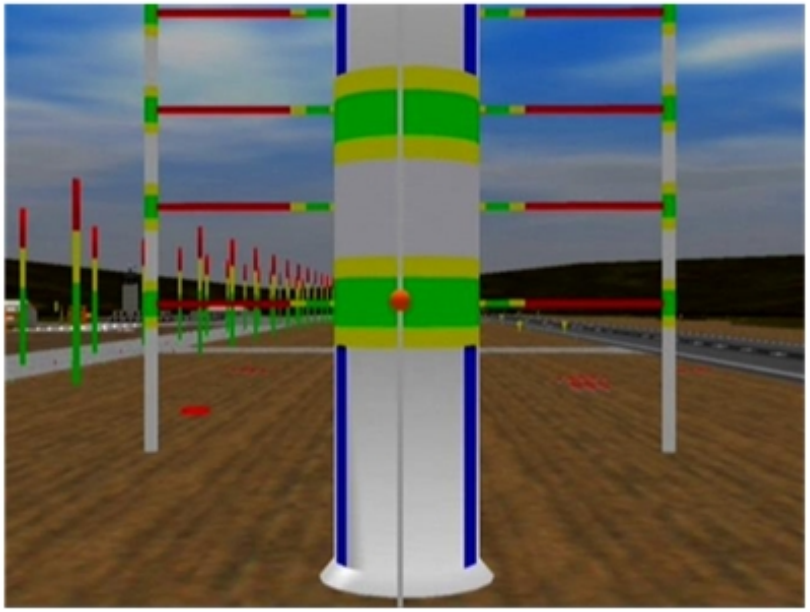
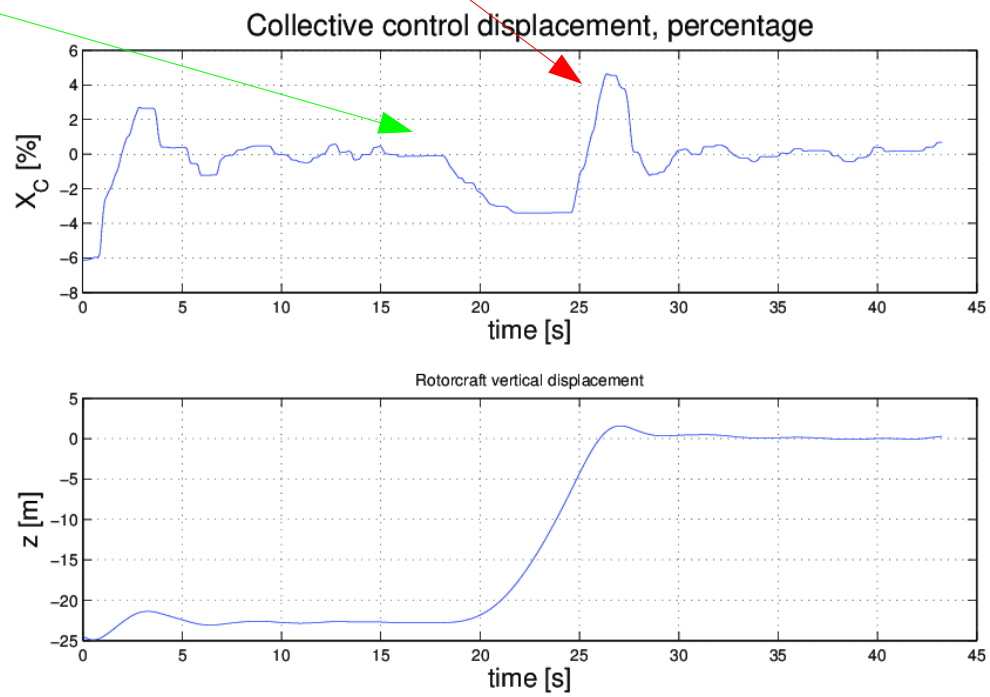
Results

Vertical maneuver (inspired by Aircraft Design Specification ADS-33)

- primary task: keep the red ball in the green band
- secondary task: move to a different level (75 ft) when told (workload, trigger)
- example trajectory (bottom) and control inceptor motion (top)
  - collective down: start descent; collective up: stop descent





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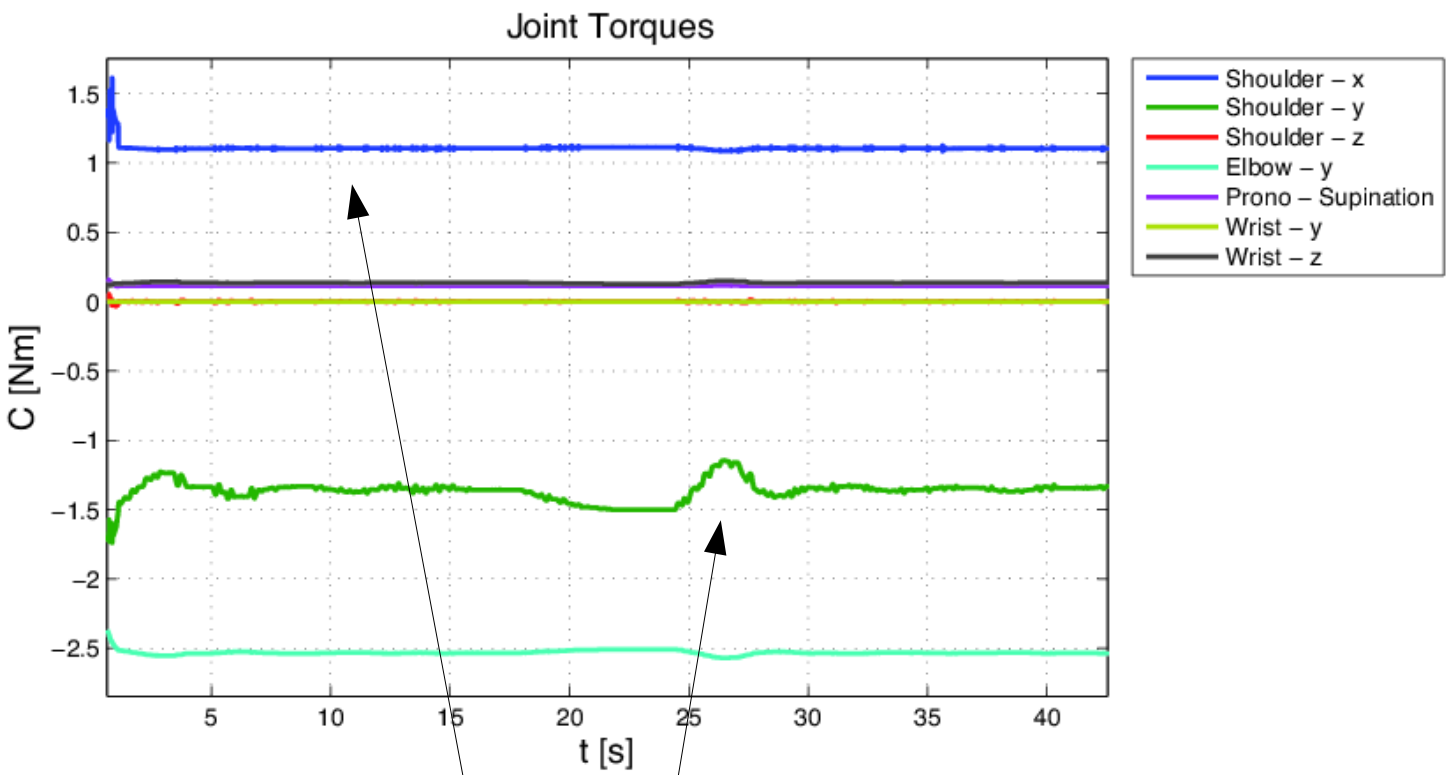
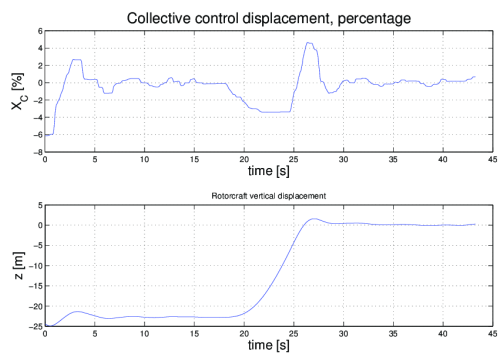
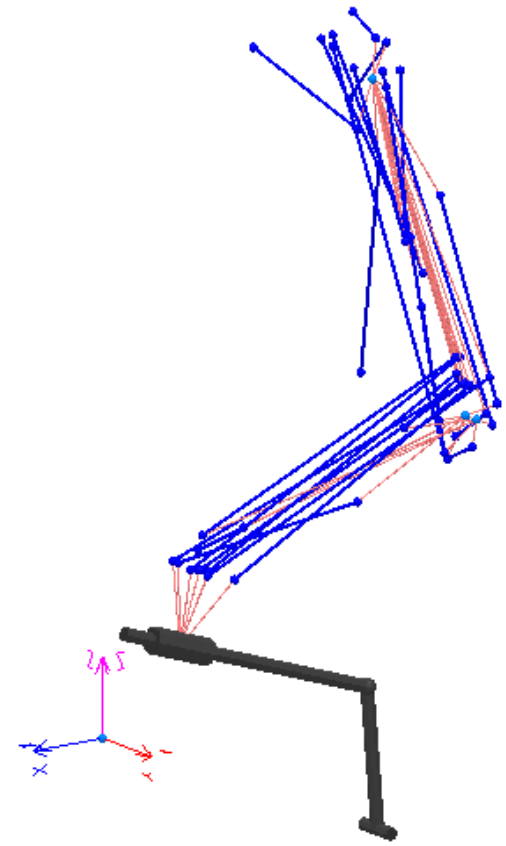


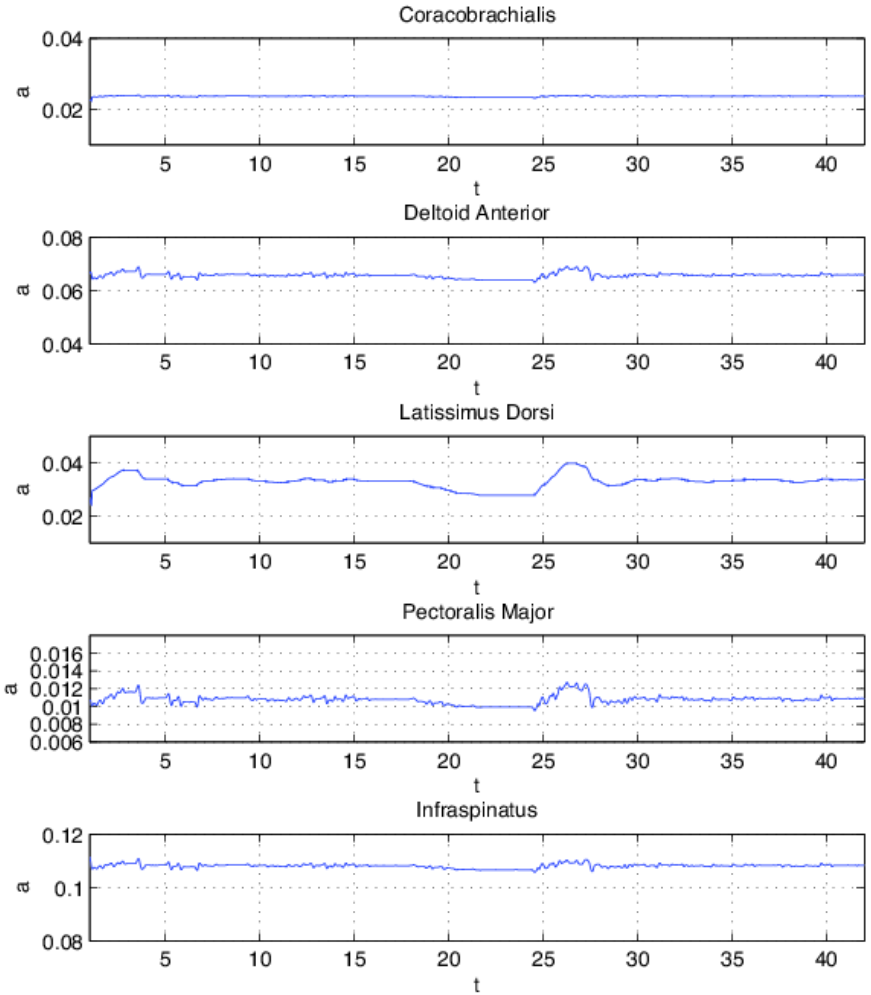
steady torques: gravity

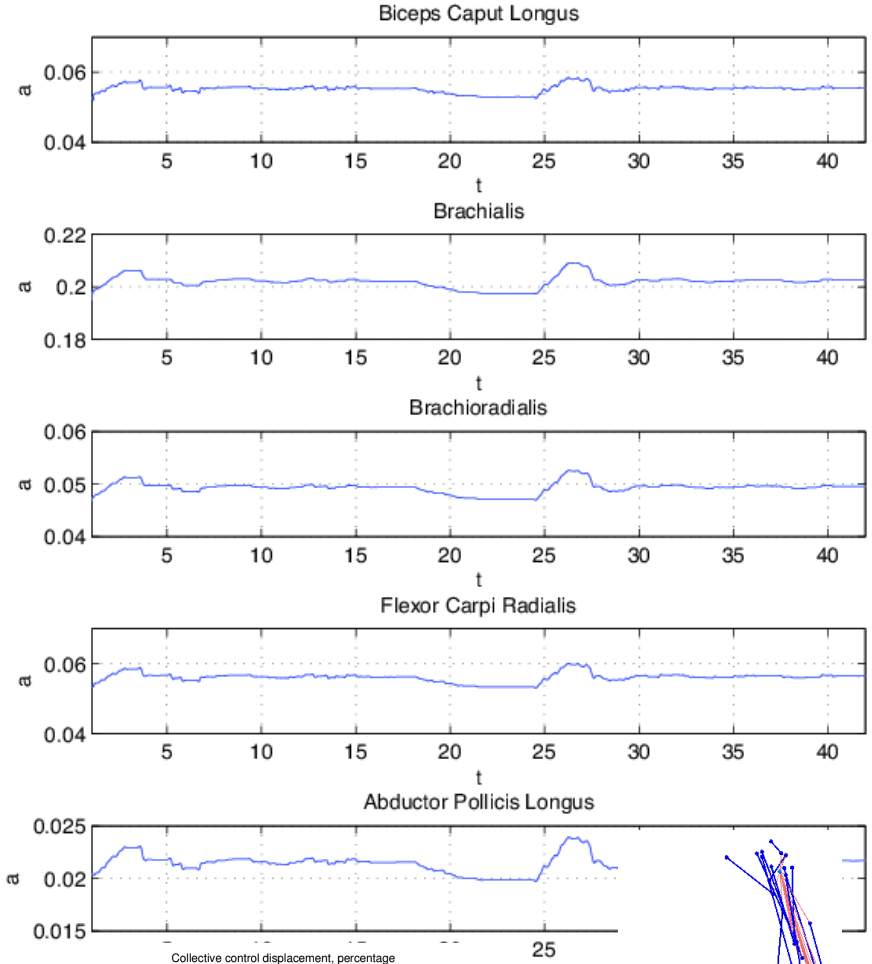
transient: maneuver

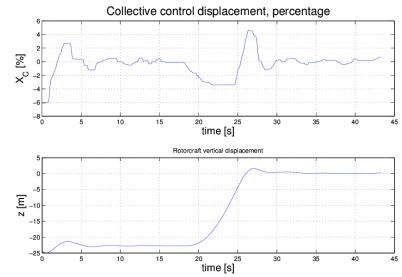


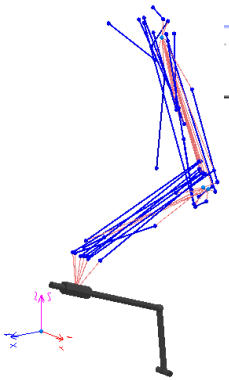


Results



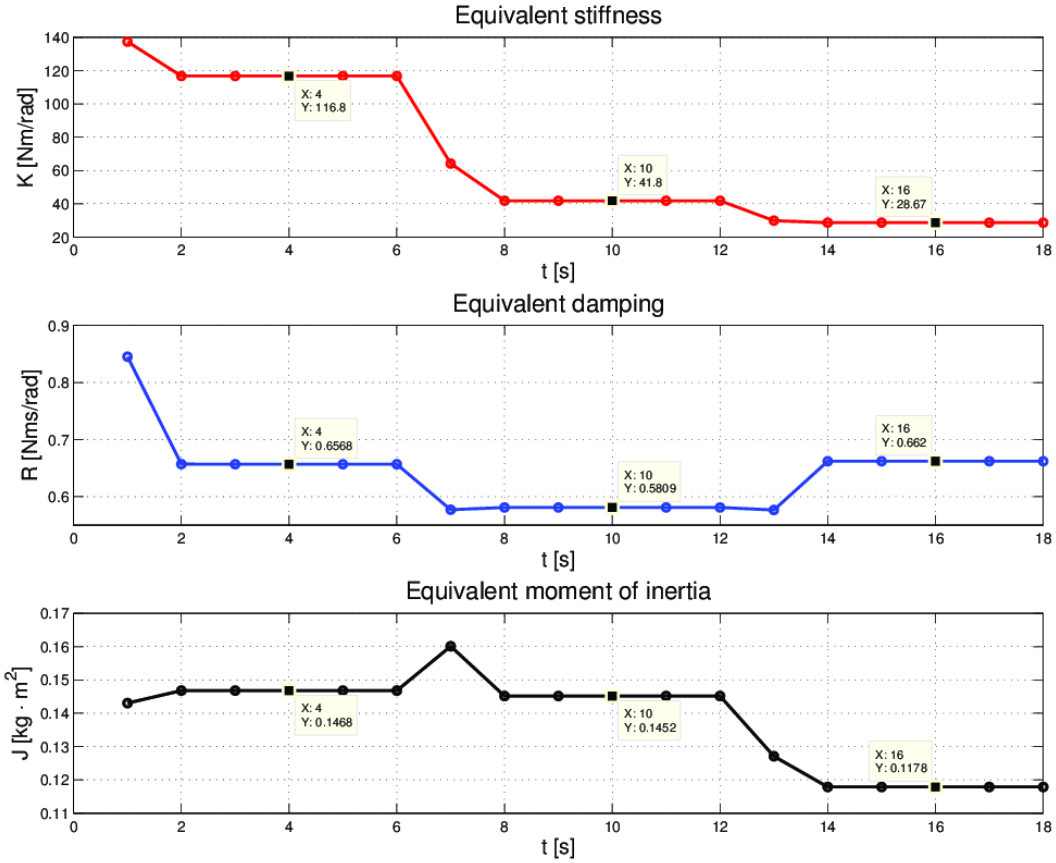






Muscular activations

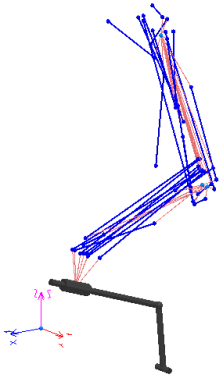
Results



10% **50%** **90%**

Equivalent mech. Properties

- configuration-dependent
- significant variability
- source of uncertainty in coupled analysis



Results

Predicted vs. measured mechanical properties from the literature

		Present	Ref. [17]		Ref. [4][a]	
			pilot #1	pilot #2	ectom.	mesom.
10%	Frequency, $\sqrt{K/J}$ (Hz)	4.49	3.61	3.71		
	Damping, $R/(2\sqrt{KJ})$ (%)	7.9	43.3	52.3		
50%	Frequency, $\sqrt{K/J}$ (Hz)	2.70	3.25	2.85	3.38	3.75
	Damping, $R/(2\sqrt{KJ})$ (%)	11.8	32.6	32.8	32.2	28.2
90%	Frequency, $\sqrt{K/J}$ (Hz)	2.48	2.55	2.03		
	Damping, $R/(2\sqrt{KJ})$ (%)	18.0	29.2	15.1		

- frequency value OK
- frequency trend OK (increases when % collective increases)
- damping value often underestimated
- damping trend incorrect (reduces when % collective increases)

[17] P. Masarati, G. Quaranta, M. Jump. Experimental and numerical helicopter pilot characterization for aeroelastic rotorcraft-pilot couplings analysis. Proc. IMechE, Part G: J. Aerospace Engineering, available online December 16, 2011

[4] J. R. Mayo. The involuntary participation of a human pilot in a helicopter collective control loop. 15th European Rotorcraft Forum, pages 81.1–12, Amsterdam, The Netherlands, 12–15 September 1989.

Results

Reflexive behavior needed to obtain reasonable equivalent properties

- muscular force perturbation

$$\delta f_m = f_{m/x}\,\delta x + f_{m/v}\,\delta v + f_{m/a}\,\delta a$$

- quasi-steady approximation of reflexive activation perturbation

$$\delta a = K_p\,\delta x + K_v\,\delta v$$

- quasi-steady approximation of reflexive muscular force perturbation

$$\delta f_m = \left(f_{m/x} + f_{m/a} K_p\right)\delta x + \left(f_{m/v} + f_{m/a} K_v\right)\delta v$$

- approximation parameters estimated from [1] (“total” vs. “intrinsic”):

Kp = 0.8 Kv = 0.003

- the force perturbation **depends on the activation**

$$\delta f_m = f_0\left(f_2\left(f_{1/x} a + f_1 K_p\right) + f_{3/x}\right)\delta x + f_0 f_1\left(f_{2/v} a + f_2 K_v\right)\delta v$$

[1] S. Stroeve. Impedance characteristics of a neuromusculoskeletal model of the human arm I. posture control. Biological Cybernetics, 81(5–6):475–494, 1999.

Results

Torque-Less Activation Modes

- activation problem underdetermined

$$A a = b$$

- SVD of matrix

$$A = U \Sigma V^T = [U_1 U_2] \begin{bmatrix} \Sigma_1 \\ 0 \end{bmatrix} V^T = U_1 \Sigma_1 V^T$$

- matrix U_2 contains activation modes that **<u>do not alter the torques</u>**
- but a linear combination of U_2 alters the equivalent compliance
- find u such that (componentwise)

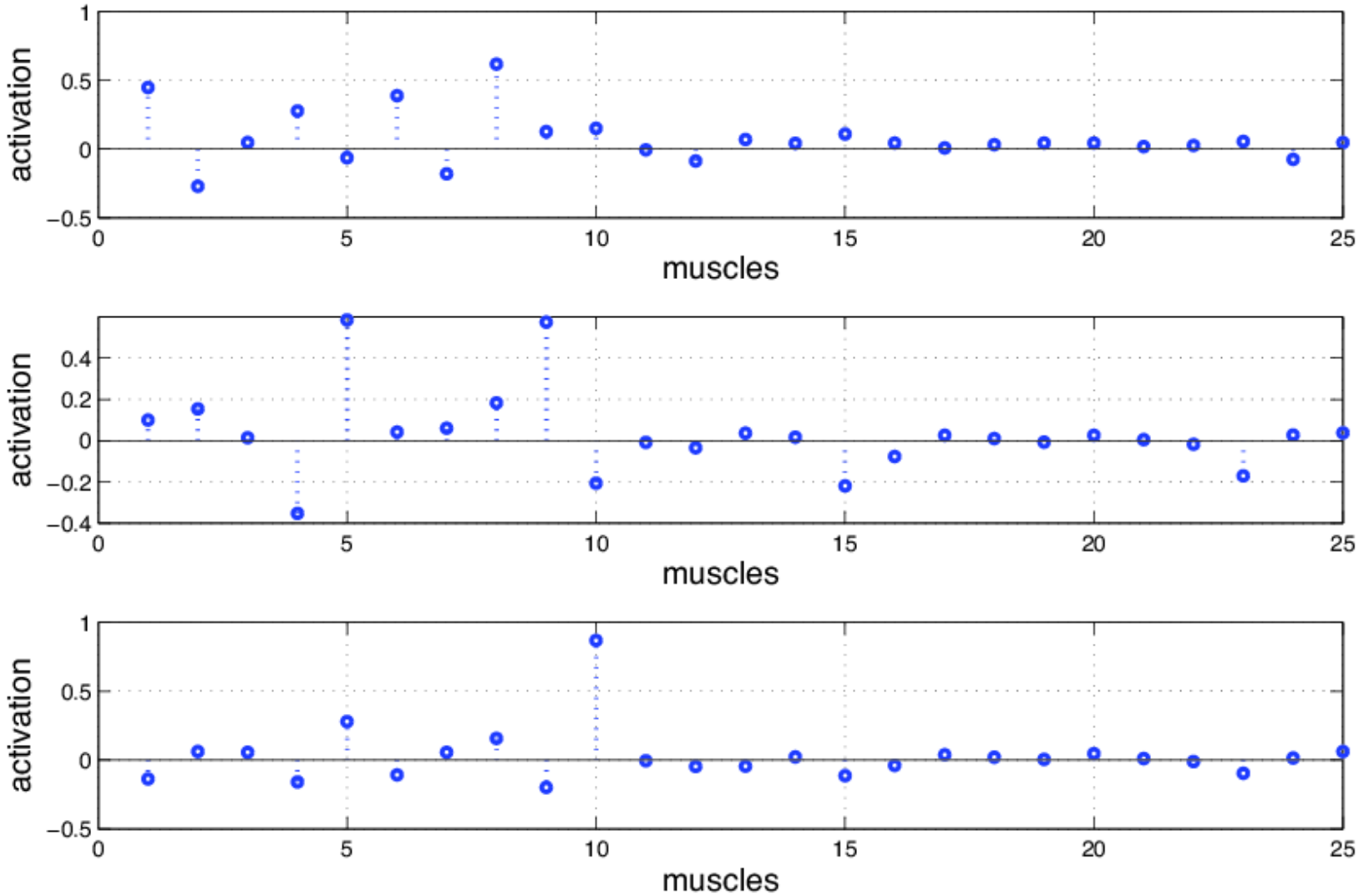
$$U_2 u > 0$$

- compute the activation as

$$a = a_{min} + U_2 u \Delta k$$

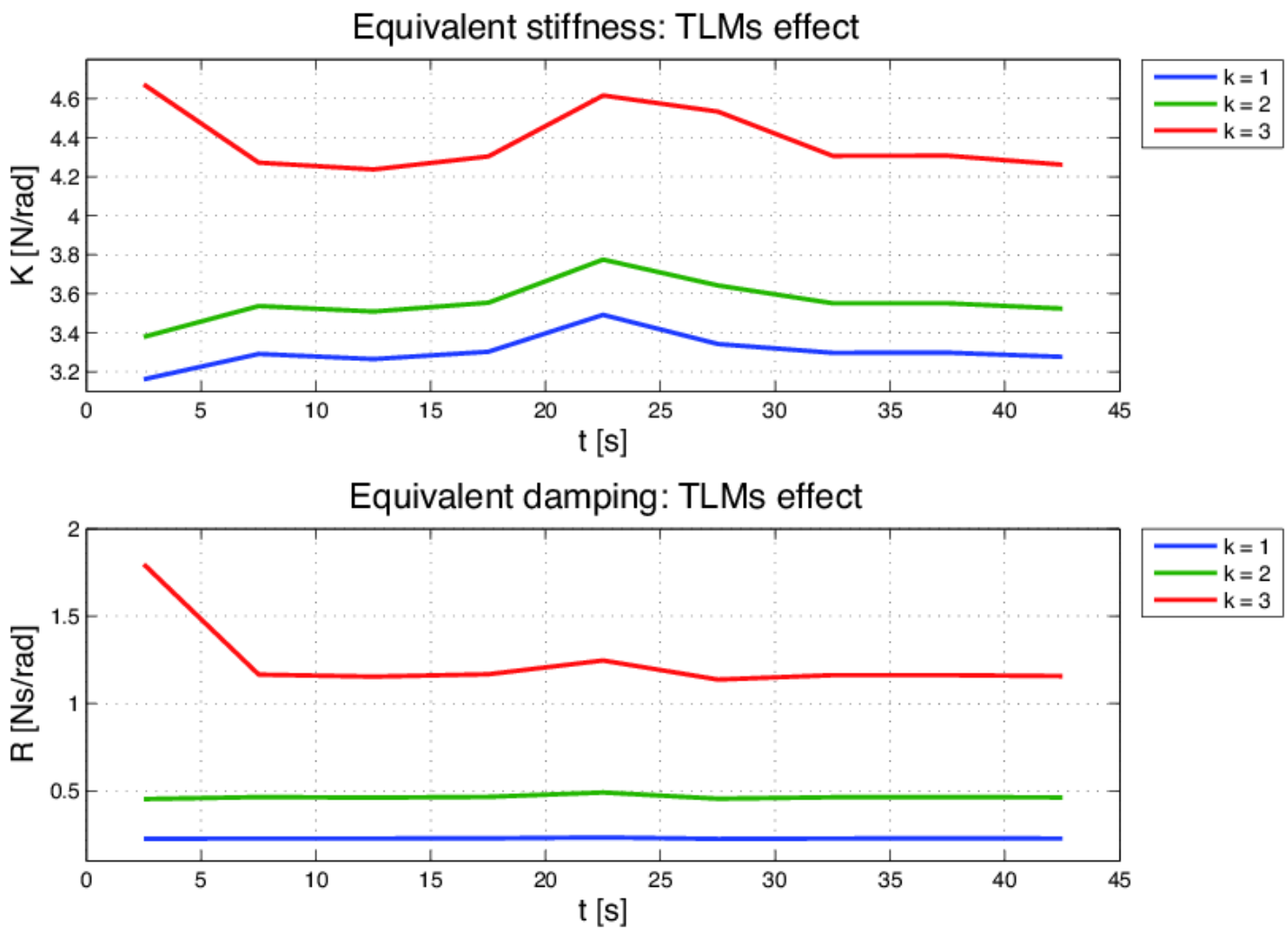
- the resulting activation satisfies equilibrium but the equivalent compliance depends on the perturbation

Example Torque-Less Activation Modes (TLAMs)



Results

Equivalent (intrinsic) compliance properties with TLAMs



Contributes to task dependence and uncertainty in BDFT

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Conclusions

- Set up of a biomechanical model of a helicopter pilot's upper limb
  - within general-purpose multibody solver
- Muscular activation computation in configurations of interest
- Equivalent compliance correlated with experimental results
- Identification and analysis of possible sources of uncertainty
  - possibility to structure and quantify uncertainty
  - Torque-Less Activation Modes (TLAM) may change stiffness and specifically damping
- Future work:
  - better understand the potential of the model
  - validate muscular activation using EMG
  - improve and complete the model (both arms + torso)
  - analyze different control inceptors layouts
  - co-simulation of coupled pilot-vehicle

Acknowledgements

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Thank you for your attention

Questions?